Office of Naval Research
European Office
93-01

NAVSO P-3678

AD-A263 397

ESN INFORMATION BULLETIN

European Science Notes Information Bulletin
Reports on Current
European and Middle Eastern Science

DTIC

In this issue, reports on...

Engineering
Manufacturing
Materials
Oceanography

Special focus...

- Electromechanical Design in Europe: Research and Industrial Practice - 1

93-08302

Approved for public release; distribution unlimited

93 4 19 134

OFFICE OF NAVAL RESEARCH EUROPEAN OFFICE

The mission of the Office of Naval Research European Office (ONR Europe) is to assist the Chief of Naval Research, the Chief of Naval Operations, and the Commandant of the Marine Corps in discharging their responsibilities on matters of general scientific and technical interest to the U.S. Navy in the United Kingdom, Europe, and the Middle East.

To carry out this mission, ONR Europe:

- Maintains liaison with European and other designated government, academic, and industrial agencies conducting research and development (R&D) of naval interest
- Assists U.S. Navy agencies in monitoring specific R&D projects
- Assists U.S. Navy personnel in mutual technology exchange under negotiated agreements
- Disseminates to the U.S. Navy R&D community matters of scientific and technical interest

---

ORGANIZATIONAL INDEX

Telephone: 44-71-409 + ext.

Office of the Commanding Officer and Scientific Director

Code	Ext.		
00	4417	Commanding Officer	CAPT John M. Evans
01	4508	Scientific Director	Dr. Arthur M. Diness
		Liaison Officers and Liaison Scientists	
12	4539	Mathematics	Dr. Robert D. Ryan
13	4131	Computer Science	Dr. Lawrence J. Rosenblum
14	4413	Polymer Science	Dr. Joseph H. Magill
15	4413	Physical Oceanography	Dr. John P. Dugan
16	4260	Electronics	Dr. Nicholas Bottka
19A	4413	Naval Air Technology	CDR Dale A. Milton
20	4413	Surface Systems Technology	CDR Barth J. Root
21	4260	Environmental Systems Technology	LCDR David B. St. Pierre
22	4260	Undersea Systems Technology	CDR John A. Sampson
32	4539	Chemical Engineering/Environment	Dr. Michael R. Overcash
34	4539	Materials	Dr. Mufit X. Akinc

U.S. Mail Address
PSC 802 Box 39
FPO AE 09499-0700

U.K. Address
223/231 Old Marylebone Road
London NW1 5TH

TELEX: (900) 7402119 ONRE UC
OMNET: ONR.EUROPE

FAX: 44-71-724-7030; 44-71-723-1837
MILNET: ONREUR.NAVY.MIL

ESN INFORMATION BULLETIN

This publication is an official publication of the Office of Naval Research European Office. It describes research that is being conducted in Europe and the Middle East.

Commanding Officer .... CAPT John M. Evans, USN
Scientific Director .... Dr. Arthur M. Diness
Editor .... Ms. Maureen L. Long

93-01

In This Issue. . .

SPECIAL FOCUS

ENGINEERING

MANUFACTURING

MATERIALS

OCEANOGRAPHY

Accesion For
NTIS CRA&I
DTIC TAB
Unannounced
Justification
By
Distribution /
Availability Codes
Dist | Avail and / or Special
A-1

DTIC QUALITY INSPECTED 4

Electomechanical Design in Europe: University Research and Industrial Practice

by Daniel E. Whitney, former Liaison Scientist for Manufacturing at the Office of Naval Research European office. Dr. Whitney is at the Charles Stark Draper Laboratory Inc., Cambridge, Massachusetts, where he is in the Design and Assembly Technology Department.

EXECUTIVE SUMMARY

The objective of this study was to assess research and applications in electro mechanical product design in Europe. Design is a high-leverage activity that can dramatically reduce the cost and time required to make and use products, both commercial and military. It is clear that advanced companies and countries see design skills, methods, and tools as strategically important. This report follows a similar one devoted to Japan.[1] Important similarities and differences were observed.

Ten companies, 13 academic research laboratories, and 4 government funding agencies were visited between April 4 and September 25, 1992. The statements and findings that follow are based on those site visits and cannot necessarily be generalized to sites not visited. They are believed to be representative of the electro-mechanical design effort in Europe.

Conclusions

Many European companies are surprisingly far behind both U.S. and Japanese companies in recognizing the need to reorganize their design processes and see the connection between design process organization and computer-aided design (CAD) software. A few have begun to form cross-disciplinary teams only in the last two to four years. But some European companies are very impressive.

Companies are in the process of revolutionizing their product design methods. Thus they want better, broader, and more sophisticated design tools and databases. Large companies face the uncomfortable choices of developing them in-house (the Japanese approach), buying basic commercial software and adding their own, or pressing the CAD vendors for more sophisticated tools.

None of these strategies is wholly successful: companies lack deep software skills, CAD vendors lack knowledge of manufacturing and design. Researchers usually are not seen by companies as direct contributors to this process. Small companies cannot even make these choices but must buy what is available. More attention needs to be paid to these problems; real progress will be made only by bringing these diverse actors together.

Good design research is going on in several academic research laboratories, but there is still not a reliable technology transfer path for new design methods. This is true, even though academic research laboratories in Europe are in some cases better connected to industry than U.S. laboratories because of the required structure of many European Community (EC) and nationally funded research programs. Several factors are involved: The companies cannot accept stand-alone software directly from universities because they want something that can be integrated with their current software. Some research offers methods (not always based in software) that are so different from current ones that entire cultures would need to change along with software. Such changes would have to include new educational methods. CAD vendors also are reluctant to acquire or support research

efforts if their customers are not asking for what is being offered. The vendors lack the resources to work on things they cannot sell soon.

The best university research observed was in the Federal Republic of Germany (FRG) (links between engineering and CAD) and in the United Kingdom (U.K.) (product data models, representation of engineering knowledge). Other good research is undoubtedly going on, but I did not get the chance to observe it.

Good deep thinking about the nature of the design process is also going on at several companies. The problems companies face and put priority on are not just short term, but in most cases arise from real gaps in knowledge. These gaps take the form of missing engineering knowledge, lack of algorithms, lack of data organization methods, and lack of understanding of all the intricacies of design processes. Furthermore, these gaps are evolving rapidly as new technologies and competition force companies to rebuild their design techniques.

However, researchers still see design the way they have for years—as a primarily engineering or geometry-driven process that occupies a single designer who focuses on a single product. They do not see it the way the companies do—focusing on conflict and tradeoffs, aware of design process integration and organization issues, providing basic engineering knowledge and hooking it to design tools, managing large teams, designing product families. Researchers need to participate more in industrial design projects to see what really happens.

Industry's view of what happens in design is therefore so different from the academic researchers' view that there is a sort of culture gap that contributes to industry's downplaying of academic research.

EC funding provides a good route for consortia of researchers and companies who want to advance manufacturing and design together. But the funds are running short; as national funds dry up, researchers are all applying to the EC. This results in too many proposals chasing too little money.

Different funding mechanisms and laboratory concepts were observed: The U.K. is forcing industrial participation in research and demanding that potential end users participate from the beginning (a sort of Concurrent Engineering of research projects). The U.K. also has launched a one-time program to fund Engineering Design Centres modeled after Carnegie Mellon's in the hope of spurring design research linked to industry's needs. The German Fraunhofer Institutes and their associated university laboratory partners interact strongly with industry, but some institutes want to keep all the industrial applications and consulting to themselves while the researchers know they need such contact with reality. The French have a national laboratory devoted to automation, but it deals mostly with software, controls, and robotics—not with design. While all of these mechanisms have advantages and shortcomings, the Fraunhofer-university partnership model seems the best because research, education, technology transfer, applications, and straight consulting are all occurring under (almost) one roof.

Major missing links in both CAD software and design research lie between graphic design on the one hand and support for business and engineering issues on the other. Conventional analyses like finite elements have long been available commercially. Deeper analyses of designs and systems, however, are not available. Researchers are trying to fill the gap with expert systems gleaned from talking to designers. But designers usually do not have good analytical bases for their approaches, so the "rules" are hard to deduce, or apparently are not there. Expert systems are thus of limited use and will remain so until more basic engineering knowledge is available and applied in design contexts.

A more important missing link in advanced design is a clear definition of a product data model. No one knows all the data that belong in it, much less how it should be structured. The idea is looming and blooming; without it, advanced design methods can neither be defined clearly, nor listed in priority order, nor brought together and dealt with by computers in a compatible way. The companies are forcing the issue onto their vendors, who do not know how to respond; almost no researchers are paying attention to it. At the end of this report is a proposal to establish a research program aimed at this problem. Such a program would need active participation and collaboration of university researchers, international standards committees, CAD vendors, and industry users.

Academic Research Activities

Research activities that I observed focus on extending the ability of computers to aid designers in various aspects of design, including developing concepts that meet requirements and generating geometric descriptions of mechanical or hybrid systems. Many laboratories are taking quite similar approaches and seem to have the same priorities.

Approaches to concept design usually take the form of "inspired sketch pads" that permit a designer to call forth library functions like "motor" or "bearing" and hook them together into systems. These systems can be simulated or analyzed in other ways; then they can be converted—element by element—into specific geometry. The analyses are supported by various rule and knowledge bases. At least, that is the goal. Most of the difficult conversions are done by the designer, not the computer.

Research into geometric descriptions comprises various efforts in feature-based design, generalized sculptured surfaces, and geometric realizations of specific engineering systems, such as machine tool spindles. Some laboratories support the designer with rule and knowledge bases; others are trying to create connections to engineering analyses like vibrations or finite elements. Efforts also exist in linking mathematical and geometric constraints to geometric modeling and feature-based design.

One U.K. laboratory is focusing on databases and data models for product design support. A data model editor permits new models to be constructed that contain both object-like properties and recursive structures. In the past, this group was heavily involved in developing new geometric modelers and CAD data conversion software. It is one of the few that strongly integrates mechanical engineering and computer science in its research.

Company Activities

I visited several companies that design and build highly engineered products and one CAD software vendor. Most of these visits revealed that few of the above research activities are of direct interest to the companies. Instead, the companies are trying to figure out how to implement Concurrent Engineering (CE), shorten their design cycles, and manage the enormous amounts of data that are typical of their products. Uniformity of data descriptions and smooth conversion from one description to another are also of concern, but workable solutions are in place. The main strategy adopted by companies is to buy commercial CAD software, add to it their own databases, analyses, and data conversion software, and forcefully press the vendors for better products.

Most companies are carefully examining their product design and organization methods. Analysis of individual parts' designs often reveals that the firm did not really know, in a *management* sense, how to design the item in question. Dramatic reductions in design time and cost have resulted from such analyses. Researchers are generally unaware of these issues, and no formal methods for analyzing design processes seem to exist.

High on companies' priority lists are stronger links between geometry, engineering, and design for business strategy. Familiar computer-aided engineering (CAE) (such as finite-element calculations (FEM)) is well supported by all commercial software; the companies are now interested in tolerances, design of multi-part products, design of product families, design for manufacture and assembly, prediction of costs, and generation of documentation. As the companies explore new CAD capabilities, they discover new kinds of applications faster than the vendors can keep up. Each vendor often has a key customer who not only drives its development but nearly saturates its programmers.

The CAD vendor I visited is aware of these needs and appears to be shifting the focus of its products toward supporting them and away from the industry's traditional focus on geometry. It will soon release a version of its three-dimensional (3D) modeling system that permits dimensioning and tolerancing, geometric constraints, and limited mathematical constraint management. Companies using other vendors' software indicate similar trends. In several cases, capabilities that are subjects of research at laboratories visited are supported commercially now or will be soon. However, vendors' work mostly deals with individual parts and seeks to link the analyses specifically to their geometry. Mathematical and conceptual design are not well supported, although research and development to generate that support is going on.

The vendor has just begun an important ESPRIT project to create assembly process modeling and assembly factory design. This project represents a turning point in CAD/CAM because it is the first really new application area since numerical control, as well as one of the first to deal with multiple parts and their interrelations.

Government Funding Trends

Both the U.K. and continental European countries are undergoing or instituting important changes in the way research of all kinds is funded. The U.K. has been reorganizing its university system, hoping to make it more responsive to actual demand from students, reducing overhead allowances, forcing more industry contributions, and imposing frequent reviews onto research projects. U.K. research strategy evolved during the Thatcher years to emphasize more collaboration with industry, more in-kind or cash contributions by industry, and an explicit requirement for technology transfer of the results. Many areas of research are scheduled for real term decreases in funding. Fortunately, the Science and Engineering Research Council (SERC), with a budget of £437M this year, is programmed for a slight increase for the next two years.

The EC has also been reorganizing its manufacturing research, removing an overlap between the ESPRIT (European Strategic Programme of Research and Development in Information Technology) program and the BRITE/EURAM (Basic Research in Industrial Technologies/European Research in Advanced Materials) program. These programs double-covered CAD, computer-integrated manufacturing (CIM), and other aspects of information technology in manufacturing for many years. EC projects tend to have many partners from several countries—a situation that can get in the way of technical progress but has been very successful in building an international research community. Additional revision of EC funding strategies and project management methods is possible.

The FRG has had to reduce research funds, in part to pay for reunification, forcing cutbacks at universities. Laboratories are being told to seek EC funds, but the success rate of ESPRIT proposals is said to be around 10 percent. The days of secure funding from the German research agencies and foundations appear over, even for the leading laboratories.

Comparisons Between European, Japanese, and American Situations

Universities

The European university design and manufacturing research laboratories, driven by the above funding trends and environment, tend to have closer relations with industry than either U.S. or Japanese laboratories. (The situation in Japan is changing toward more cooperation with industry, especially at the national universities where government support is thin.) The European universities, especially in the FRG, have faculties with long industrial experience. These professors often express dismay at the content of U.S. research papers and Ph.D. theses ("all math, no applications"). However, the focus of university research on the individual designer seems to be the same in all three regions, in contrast to industry's focus on the business issues.

Within this context, university research is similar in most respects to what is found in Japan and the U.S., inasmuch as communication between these researchers is frequent and strong. English is the "lingua franca" of world research, e-mail is in wide use, and inter-region travel and exchanges of visits are common. Only a few laboratories anywhere recognize the need to merge engineering, CAD, and computer science disciplines in design research. Only a few laboratories are taking on even a hint of the management issues (resource management, risk management, design process structure, product data models) that industry knows are at the heart of the problems they face.

In this regard, the Massachusetts Institute of Technology (MIT) Leaders for Manufacturing (LFM) program may be unique, since it aims to merge the Engineering School and the Management School in this topic area. Nothing like LFM was encountered in Europe or Japan, although the U.K. teaching company program is similar on a smaller scale. Teaching companies are one-on-one arrangements between a firm and a university, whereas LFM has about a dozen participating companies. It includes both a coordinated

engineering-business curriculum and student theses jointly supervised by faculty from both schools.

Companies and Government Funding Patterns

There are wide differences in the maturity of design methods and tools in different European companies of similar size. In Japan, similar size companies were more similar in achievements, approaches, philosophy, and tools. The most impressive companies visited in Europe (Volvo, Aerospatiale, Peugeot) appear comparable on some scales to the best Japanese companies, while other firms have just discovered the essentials of Concurrent Engineering and its associated organizational requirements in the last two years or so. The same situation applies in the U.S.

Companies have better opportunities to work together and with universities in Europe than in the U.S. because of the availability of EC programs aimed at manufacturing, design, CAD/CAM, and computer-integrated manufacturing (CIM). Although EC programs like ESPRIT have been criticized for achieving less than expected in the way of long-term real economic growth, they have nevertheless achieved several vital things that Europe has not had in the past:

- increased cooperation across national borders,
- links between companies that may someday merge, and
- an institution (the EC) that encourages cooperation in both applied research and technology transfer.

The U.S. does not have government institutions devoted to applied research and technology transfer in design, manufacturing, and CAD/CAM. Many smaller programs with different objectives address portions of the spectrum [e.g., the National Science Foundation (NSF) and the Office of Naval Research (ONR) for basic research, MANTECH (Manufacturing Technology) and IMIP (Industrial Modernization and Investment Program) for introducing new manufacturing technology into defense contractors, Department of Commerce Advanced Technology Programs for industry]. But these do not address some important collaborations or the full range of research, technology development, transfer, and hardening. Also, their commitment to civilian industry varies, depending on the program. We have no national laboratories devoted to this topic, such as LAAS (Laboratoire d'Automatique et d'Analyse des Systemes) in France or the Fraunhofer Institutes in the FRG.

Technology Transfer

Technology transfer of new design methods and tools follows an uncertain and poorly documented path. Users look to CAD vendors for such tools so that they will be compatible with millions of lines of existing code and hundreds or thousands of trained users. Also the users look increasingly to vendors for products that are outside their traditional range of geometric modelers, requiring experience and knowledge they do not have. One would think that they would turn naturally to researchers for high-leverage help.

However, this has not happened very much, often because the researchers' results are too far ahead of practice. "Our customers are not asking for that," is the reply often heard. Naturally, the researchers cannot go directly to the users because the former cannot offer the software compatibility or robustness that the latter require.

EC and U.K. programs have tried to incorporate technology transfer plans and commitments, whereas NSF programs, for example, do not. However, the paths are not well understood, and current ones appear inadequate. Because companies actually face the problems and have the clearest view of them, some "problem definition transfer" in the opposite direction, to the researchers, is also needed.

Japan Redux

In the year since I visited Japan, I have had some confirmation of my conclusions. In addition, discussions with a Briton who just returned from a year's stay with Mitsubishi Motors reveals that we may still not appreciate the depth of Japanese concepts like Just in Time (JIT) and Quality Function Deployment (QFD). He quoted Toyota as saying that even other Japanese firms do not fully grasp JIT. The detailed QFD notebooks he saw at Nippondenso amazed him, as well as the depth at which the engineers there understood the concept.

Examples of failure mode analyses were so crisp that they implied a highly developed ability to identify the critical issues and ignore the rest-the result of careful attention and years of record-keeping.

Do We Understand the Design Process—and Are We Doing the Right Research?

The Main Research Gaps

Industry appears to be seeking research that makes two essential connections that are rarely studied by researchers: connections to business and to engineering. Business connections involve both "mundane" topics like predicting the cost to fabricate and assemble something as well as challenging "business strategy" issues like how to design a family of products. Cost dominates industry and is mainly ignored by researchers. Family design, to take an example, requires mustering market data, gathering information about past designs, and deciding how to cover a wide range of varieties with a limited number of subassemblies and modules. Some of these requirements are completely new and require new methods.

Engineering connections include being able to understand, evaluate, and analyze structures (such as shafts and their bearings) or multi-technology items (electro-optic, electro-hydraulic). Understanding that a preloaded bearing is in a load path requires knowing that abutting surfaces can support compressive loads; that load paths form loops of compressive and tensile forces around which the force sums to zero; that threaded fasteners can exert compressive force; and so on. In place of this essential engineering knowledge and supporting analyses, academic researchers are trying to substitute expert systems whose rules are gleaned from practicing designers. The results are falling short of expectations, probably because the designers do not understand the engineering at a deep analytical level and because the researchers do not realize this. In addition, the engineering knowledge may be too incomplete to permit significant design aids to be developed.

The companies visited emphasized business issues over engineering ones. In the last few years they have been driven to re-examine their design processes by the force of outside competition, especially from Japan. The Japanese appear to be from 2 to 15 years ahead in this respect, depending on which company one evaluates. This re-examination has exposed multiple inefficiencies in typical design processes. So far, these inefficiencies have turned out to be specific to the item being designed and focus on missing or late information. Individual items' design processes are now being attacked as if they were manufacturing processes that need efficiency experts. One firm referred to "just-in-time design," meaning that the right information is available at the right time.

Companies are understandably looking to computers to help as they recreate their design methods. Such help must come from facilities not emphasized in the past by CAD vendors or researchers. In Japan[1] the larger companies have responded by writing their own software with help from computer companies. In Europe almost no one has taken this approach. In addition, companies in both Europe and the U.S. appear ill-prepared to look far enough ahead to recognize useful elements or trends in ongoing design research.

Researchers seem to be unaware of the forces and events driving the companies. They see design the same way they have for years: as an individual activity that needs to be supported by computers—to design a single product, a single person must reduce a set of requirements to a geometric description, observing the needs of manufacturing and revising the design as necessary to achieve those goals. Companies see this aspect of design but also see something most researchers do not: a complex multi-person activity that must be managed, dominated by huge masses of data, and having sharp conflicts between the needs of various constituencies.

Both researchers and companies agree that design is a progressive process, but the researchers see it as an orderly quest. By contrast, the companies live with wild gyrations in risk, strong differences in approach by different design team members, and problems too big for one or even a few people to comprehend and manage. These differences are not just a matter of style but represent real gaps that strongly affect what researchers and industry, respectively, think computers will be able to contribute as well as how those contributions should be described and achieved.

The experience of actually designing a complex item appears indispensable if one is to comprehend the process and aim research at its most difficult points. Too few design researchers have such background. The exceptions are immediately obvious. In the FRG, for example, most professors are former industry designers or engineers, and bring a very technical attitude to their research, with interesting results. But many of these people got their industrial experience before major advances in computer science occurred, and they do not integrate such knowledge with their research. This gap is apparent in most other countries as well. Thus actual design experience is necessary but not sufficient. New collaborations are needed, not only between researchers and companies, but between engineering and computer-oriented researchers.

An Emerging Research Priority: The Product Data Model

A major priority for both companies and researchers is the notion of a product data model (PDM). In the past, the drawings constituted the model. The shortcomings of drawings, and their computer incarnation as two-dimensional (2D) drafting, are now well recognized. Adequate geometric representations now exist in the form of verified 3D surface and solid models. So, in industry, the focus has shifted to the other 90 percent (Note: this is my "over-estimate" made for emphasis; while no detailed study has been made and a metric has not been suggested, the 90:10 ratio offered here is likely to be fairly accurate) of the information needed: tolerances, engineering calculations, process descriptions, design process information flows, assembly, and so on. Indeed, industry people seem to be coming to the conclusion that the PDM in some sense describes or is even driven by the design process. PDMs therefore represent a fundamental resource for companies interested in providing a solid base for improved product design as well as a formidable intellectual challenge for researchers. We need to understand what belongs in a PDM or even if its name should be changed to Product-Process Data Model. The best source for finding the answers is industry.

However, companies are revolutionizing their design methods, recognizing the need for new kinds and arrangements of data, so the PDM is a rapidly moving target. This fact not only causes problems for researchers but also for the PDES/STEP (Product Data Exchange using STEP) activity, which aims at creating a standard for exchanging product data. Any attempts to define product data must track this target.

The fact that the "other 90 percent" includes a lot of traditionally *nonproduct* data is interesting because in some quarters (mostly among people with information technology backgrounds) it is hoped that there exists such a thing as *pure* product data. The model for this hope is VLSI (very-large-scale integration) where it is said that one can design purely in terms of function, leaving out any concern for process as long as the "design rules" are obeyed. There are many advantages to pure product data, and thus the goal is worth pursuing. At present, however, few in the electro-mechanical design community, either industry or research, would be likely to share this hope.

A major theme of the next few years in design research will be the question of what really belongs in a PDM and how it should be represented. Answers are coming in so fast (design process structure, engineering fundamentals) and from so many directions (industry, researchers, PDES/STEP) that we are presently in a state of divergence rather than convergence. As the question becomes better understood and answered, dependent issues like feature-based design, representation of engineering knowledge, encapsulation of design processes, and management of differing design versions in Concurrent Engineering will be easier to deal with.

INTRODUCTION AND BACKGROUND

Study Goals

I spent from 3 April to 26 September 1992 as a liaison scientist at the Office of Naval Research European Office while on leave from the Charles Stark Draper Laboratory, Inc., Cambridge MA. The focus of this tour was university research and industrial applications of computers in product development, particularly development of complex electro-mechanical products. Thus it is a direct follow-on to my study of the same topic in Japan.[1] The issues are to determine what people think the product development process (PDP) consists of, what methods are appropriate for implementing modern PDPs, how computers can help, what is missing from commercially available computer tools, and what the researchers think the knowledge gaps are.

Design, properly defined, includes a great deal about manufacturing. However, the report deals with research about manufacturing processes only in such contexts as CAD/CAM interfaces or design for manufacture, not as separate topics, research projects, or visit sites.

Within the total spectrum of design, the focus is on "design as an enterprise activity" rather than "design as something a creative individual does." This focus accurately reflects the priorities of essentially all the sites visited. That is, the notion of "what designers really do" is set in the business context (define a product, get a computer model of it, estimate its cost, stress, manufacturing problems..., define the manufacturing and assembly processes, etc.); it is not set in the ergonomic or psychological contexts (what is creativity, how do we aid it, how do designers think while designing...).

Furthermore, the focus is on primarily mechanical engineering approaches rather than primarily information technology (IT) approaches. This focus, too, accurately reflects the sites visited, which in turn reflects my choice of sites to visit. Nevertheless, some sites visited have integrated IT partners and approaches very tightly while others have not. That is, the bias in my site choice did not create overwhelming bias in the findings.

Methodology

Compared to the Japan study, this one differs in several important ways. First and foremost, more emphasis is placed on university research, although many companies were visited. Second, unlike in Japan, many of the sites are new to me, so I do not have the benefit of continuity over many years of visiting the same places. Third, this report inevitably lacks the single focus that the Japan report had.

This last point deserves a little discussion. While Japan is known for its homogeneity, Europe is known for its diversity, and the Europeans are still discovering how diverse they are. In addition, design research is known for its lack of consensus, so one finds a wide variety of problems being pursued. Third, and quite interesting, the companies visited are in widely differing states of maturity in their design methodologies. I believe that some did not really understand what I was trying to find out, and were unable to respond to my questions. *This never happened in Japan.* Every company visited there knew exactly what I was after, prepared careful presentations to me, knew who to invite to meetings with me, and responded in detail to most questions.

The result of all these factors is that my European visits had a more ad hoc quality than the visits in Japan, which by contrast covered almost the same material each time and therefore permitted comparisons to be made between sites. In this report I am obliged to make my own synthesis of what I learned, although this is a welcome opportunity. I use this opportunity at several points in the report to note where industry and universities differ in their assessment of needs and to offer my own suggestions on how to focus future research. The goals of this focusing are to reduce some of the diversity, create some consensus, and pose a set of questions that will address industry's needs while bringing out some important long-term research issues.

In all of the report that follows, it is important to note that my statements are based on research laboratories and companies actually visited—they cannot necessarily be generalized to others. Readers are requested to keep this in mind when they

read "researchers," "companies," and other such terms.

Structure of the Report

The report is broken down into four main sections, and a number of topics are dealt with along the way:

1. What companies are doing
   - what problems do they think are important
   - how are they approaching these problems
   - is university research of any use to them
   - where are they with respect to the Japanese and Americans in terms of design methods and technologies in use, and what strategies do they debate (make or buy CAD, for example)
   - where are they along the maturity spectrum of Concurrent Engineering (CE)
   - in what directions are they pushing the CAD vendor community

2. What universities are doing
   - is there any consensus on the research issues
   - what research is being done
   - what contacts do they have with industry and what difference do these contacts make in their research topics or methods
   - are funding and research management trends affecting research topics or choice of partners

3. What governments and the EC are doing
   - are funding trends up or down and where will future funds come from
   - are projects being managed or just funded; will research agendas and centers of excellence be managed or just peer reviewed
   - are the political objectives (internationality, many players) getting in the way
   - are the results being used

4. Larger Issues (dealt with along the way and summarized at the end)
   - Is mechanical or mechatronic design really different from integrated circuit (IC) design; if so, how, why, and will it always be different
   - Do we know what should go into a product data model: how much information about non-product things like tooling, fixtures, or the design process itself should be included (the ideal, from the IC world, is that design and manufacturing processes are separate)
   - Is industry ahead in thinking CE through and what do the universities think about CE
   - What is the right structure for a research project and a research group in design/manufacturing (models include the Fraunhofer Institute in the FRG, the U.K.'s Engineering Design Centres, ESPRIT consortia, Cranfield Institute of Technology's centers of excellence)
   - Are any technology transfer routes being set up: what, and from which of the research groups/structures
   - Can universities really do design research or should they just be centers of excellence while industry defines the broad problems.

Redux of the Japan Study

To set a context, here are the goals and main findings of the Japan study.[1] Based on conversations with Japanese who have read it, the findings are not only basically correct but the conditions observed in 1991 still seem to exist in 1992.

The Japan study sought to answer the questions:

- What is the main outline of the product development process, starting from conception and concluding with construction of the manufacturing facility?
- What computer tools support this process and where do they come from?
- How long does the process take and how many engineers are involved?
- How are the needs of manufacturing and other interests integrated into the design process and how are the inevitable conflicts between performance, cost, and manufacturability resolved?

- What are the main challenges to intelligent and successful product design (e.g., product diversification, business forces, international teams, exploiting automation...) and how do companies meet them now and plan to in the future?

Important findings in Japan were:

1. Advanced companies write their own design software to suit their carefully conceived PDP, since such software cannot be bought; from the smallest company visited (1700 employees) to the largest, all had all their engineers on networked terminals
2. The PDP itself is the subject of "continuous improvement" carried out by full-time staff who are former engineers
3. Design teams are small, usually 10 - 15, rarely more than 30, even for complex products like autofocus cameras having 500 to 1000 parts
4. Integration of design process steps into monolithic software systems with common data access is the main priority, with detailed accuracy of individual modules having lower priority
5. Design for assembly is being used in innovative ways
6. Japanese university engineering education is general and shallow, giving graduates a broad and integrated view; the companies exploit and extend this by rotating the employees through many work assignments, creating "universal experience" that implicitly ingrains the ideas of Concurrent Engineering; deep expertise is shared over a group rather than being the property of an individual

WHAT COMPANIES ARE DOING

European Companies Visited and Their Main Concerns

The European companies visited, and their main product lines, are listed in Table 1. Each company manufactures a highly engineered product in a variety of models, and each makes heavy use of computers in the process. All pay attention to their PDP but are at different stages of maturity. All see the PDP as a process, and some are being innovative in finding new ways to think about it. One firm has recently completed reorganizing itself from a department-oriented structure to a project-oriented structure—"We learned a lot from our friends in manufacturing. We used to do design the way a job shop operates. Now we do it the way a manufacturing cell works."

Status and Maturity of Product Development Methods

Although all the companies are working on improving their design methods, it is clear that some have begun thinking about team design, concurrent engineering, and other new methods only in the last two to three years, while others have been at it for as long as ten. This puts some of the companies nearly on a par with the best Japanese companies in duration of effort if not necessarily sophistication of approach, while others are just out of the starting gate.

Many companies have particular concerns that are based on the character of their product lines. Several (AMP, Rolls-Royce, Siemens, Telemechanique) report that their task is to design a *family* of products rather than a single product. This has interesting implications for required design tools and product data, as discussed below.

In addition to improving their product development processes, all the companies visited are concerned with

- converting and transmitting data between different computer programs and companies (most have written their own, and several industrial or national consortia often share the methods);
- getting software that will exchange data easily (including "hot links" that would, for example, put current statistical process control data right on the drawing for the designer to ponder);
- converting designers from 2D to 3D software, (mostly a user interface problem);
- improving the ability of computers to help their designers do engineering—as opposed to geometry—work;

Table 1 - Companies Visited

Company Name	Main Product	Example Visit Topic
Aerospatiale	Airbus	Folded parts, assembly process modeling
AMP, Inc.	Electrical and fiber-optic connectors	High-precision butt joints for fiber optics
Arthur D. Little, Inc.	Management consulting	Concurrent Engineering
Dassault Systemes	CAD software	CATIA solid modeler with new capabilities for engineering
Peugeot	Automobiles	Bond Graph model of automatic transmission
Rolls-Royce	Aircraft engines	Internally cooled turbine blades, assembly process modeling
Siemens	Electrical machines	Family of large motors and generators
Telemechanique	Automation systems and controls	Family of motor controllers
Volkswagen	Automobiles	Body panels
Volvo	Automobiles	Design process for engine, steering knuckle, connecting rod

- pushing the CAD vendors to come up with solutions to these problems; and
- understanding "expertise" in the sense of how to compose design teams, how to create people with expertise, and how to capture expertise in computers.

To see more easily where different companies stand in their PDP improvement process, it is useful to define four stages of maturity in Concurrent Engineering:

Stage 1: Cross-disciplinary teams are formed, including people who have never talked to each other before during a product design exercise (e.g. market researchers, engineers, manufacturing and quality people, purchasing agents). They discover what the real design requirements are and, more important, that these requirements conflict. "Fights break out immediately," said one of my Japanese hosts.

Stage 2: Once the fight/discovery stage is passed, the team discovers that they really do not know how to design the product. Of course they know how to do all the calculations, given the right information. But the *process* by which that information is generated has grown up ad hoc. No one has a clear picture of all the information that is needed or the problems that the existing decision structure causes downstream. For example, a decision structure based on "generate-and-test" will cause the process to iterate or oscillate with a dynamic of its own. The engineers are whipsawed and conclude wrongly that management can't make up its mind. Usually the designers and their management cannot fix such structural problems themselves, and outside facilitators are needed.

Stage 3: When it is understood that a wholesale redefinition of the design process—its decision sequence and its information flows—is needed, the group and its facilitators can analyze the process and spot reasons why it is inefficient. A few formal analysis methods exist for helping this process, but familiar project management tools like PERT/CPM are usually of little help. All of the designers participate in this activity, giving them

and their superiors their first collective and comprehensive view of the process, one they can agree on. The result is a much more detailed description of the process than they have ever had before. This activity can save 25 percent or more of the design/development time. Very few companies have recognized the need for this stage, however. The experiences of Volvo, described below, are among the best encountered during this study.

Stage 4: A main output of Stage 3 is identification of key tasks (decision drivers, time wasters, long lead activities, steps that generate revisions and redesigns). In many cases, redefining the process can reduce these problems; in others, a new computer tool or tools will be needed. For example, once it is seen that a critical top management final review always causes big design revisions, the big review can be replaced by a series of mini-reviews spread out along the process. Again, if it is determined, as in Japan, that assembly should be analyzed as part of concept design, then software can be developed to aid the required decisions. Such activities can save another 25 percent of the time.

The importance of the above discussion for the research community is that it describes a critically important activity that researchers are apparently unaware of and for which there are hardly any tools and no solid scientific basis. The state of the art is that execution of stage 3 and stage 4 appears to be a *generic* approach that has to be repeated for each *specific* item being designed (turbine rotor, steering knuckle, motor controller). The data, information flow, and calculation requirements generated for each item usually do not give much clue about those needed for the next item, at least not yet. Perhaps after this process has been repeated many times and the results compared, a more generic structure or analysis approach will emerge.

Representative Company Activities

Volvo

All of the companies visited appear to be in or past stage 1, but only one appeared to be in stage 3 - 4, that one being Volvo (for a more detailed discussion see, "Dramatic Reduction in Lead Time at Volvo Based on Restructuring the Design Process and Introducing Computers," *ESNIB*, this issue). For a relatively small company, Volvo has made substantial progress in design technology. In some areas, such as collocated design and development and paperless design processes, Volvo is on a par with some Japanese companies and ahead of some European and American rivals. They are keenly aware that design is a process just like typical manufacturing processes. Volvo is also the first place I have visited where there is an appreciation for the fact that conflict is an essential part of design, not a symptom that people can't get along.

In one sense, Volvo's concept design process is more computerized than Toyota's since stylists can work directly on the computer rather than with sketches. The software being used for this (ALIAS) permits the stylist to deform the surface freely by grasping control points on it. [Note that this "same" capability is the subject of research at the Massachusetts Institute of Technology (MIT) and is called "new" to CAD by Dassault Systemes. I do not know whether I am missing an important point here or whether research is not as far ahead as researchers think]. ALIAS is fully compatible with CATIA, the solid modeler that Volvo is gradually standardizing on.

Some features of CATIA limit the amount of factory simulation Volvo can do. For example, robots can be programmed from part data to spray paint but not to weld car bodies. Other software is used for that. Also, CATIA cannot hold large solid models of many parts so that interference checks (part-to-part, part-to-robot, etc.) can be done. Many Japanese and European companies I visited said the same things about solid modelers in general.

However, CATIA's mathematically firm solid model permits Volvo to use data conversion and communication with suppliers with confidence, whereas they have no such confidence in converting ordinary 2D models made by drafting software. This shows that research efforts to create logically consistent 3D models have paid off in a serious way. CATIA's historical evolution from 3D to 2D may put it in a good position to solve the 2D conversion-transmission problem.

Altogether, Volvo estimates that the use of CAD and numerical control has cut body engineering time by 50 percent. They are now turning their attention to engines and transmissions. The

process of improving the power train design process appears to be following a more deliberate path than in body engineering. The process has a name: Integrated Engineering. They have developed a procedure for accomplishing it and tried it out on some individual parts. Now they are in the process of trying it on entire engines. For this purpose, the CIM department has taken on the responsibility for modeling design processes, redesigning them, and proving to the designers that they can cut 50 percent or more from the time they currently take.

Two projects have been completed: a connecting rod and a steering knuckle. Both are critical engineered parts where weight, strength, and safety are vital issues. The design process for each was cut from typically 40 weeks to 20 or less. They are now confident that similar reductions are possible everywhere at the single part level.

The steering knuckle (Fig. 1) used to be a long and highly iterative part to design for two basic reasons. First, some design decisions had to be revised after the supplier was chosen. Second, some design details often led to the need for careful hand finishing of the parts to avoid stress concentrations and possible field failures. Both of these caused extensive delays while the part was redesigned and reanalyzed.

The supplier-related problem is especially interesting. The part is forged, and the issue is to choose the draft angle of the forging die. This angle is directly transferred to the finished part, so any FEM analysis will be affected by choice of draft angle. These analyses take a long time but must be redone if the angle changes. Also, redefining the CAD model to change the angle is cumbersome. Unfortunately, the supplier who won the contract often could not deliver at the original draft angle (smaller angles are harder to achieve). Thus the lengthy design and analyses had to be done over. To avoid this iteration loop, the integrated engineering team had to convince the purchasing department to permit the supplier to be chosen early in the design process, before a design existed and thus before the supplier could bid. Competitive bidding is thus ruled out. The net effect is still a win for Volvo because of the reduced design time.

This is not yet a scientific process and may never be, but some patterns can be discerned. These seem to me to be:

- identify all the necessary design steps and the information they require and generate;
- find where this information is really available (not just at the official end of a given step in the process, but often earlier in that step) and decide if it can be made available right away to subsequent steps that need it;
- find sources of iteration and identify the real reasons;
- identify information whose availability is time-critical (if delayed, will delay the design) or content-critical (if revised, will cause large changes in the design) and separate it from less critical information, even if both used to be grouped in past design methods;
- find opportunities to work in parallel;
- find long lead time items and try to start them earlier (noting that the information they will need must also be provided earlier);
- find precedence chains that can be broken so that tasks can be resequenced (this requires classifying constraints, much as Nippondenso does, into "must have," "would like," "due to physical law or material property," and so on); and
- find ways to design-out problems that will take a long time during manufacture and assembly (a wasted minute making each of a million parts adds up to a lot of time, more than may be needed during design to avoid the waste).

Note that, in the steering knuckle case, "having the supplier on board early" is motherhood, but "deciding the draft angle early" is *the* critical decision that is accomplished once the supplier is on board.

Volkswagen

Space does not permit a lengthy description of this large and interesting company. Although it is aware of the issues discussed above and has

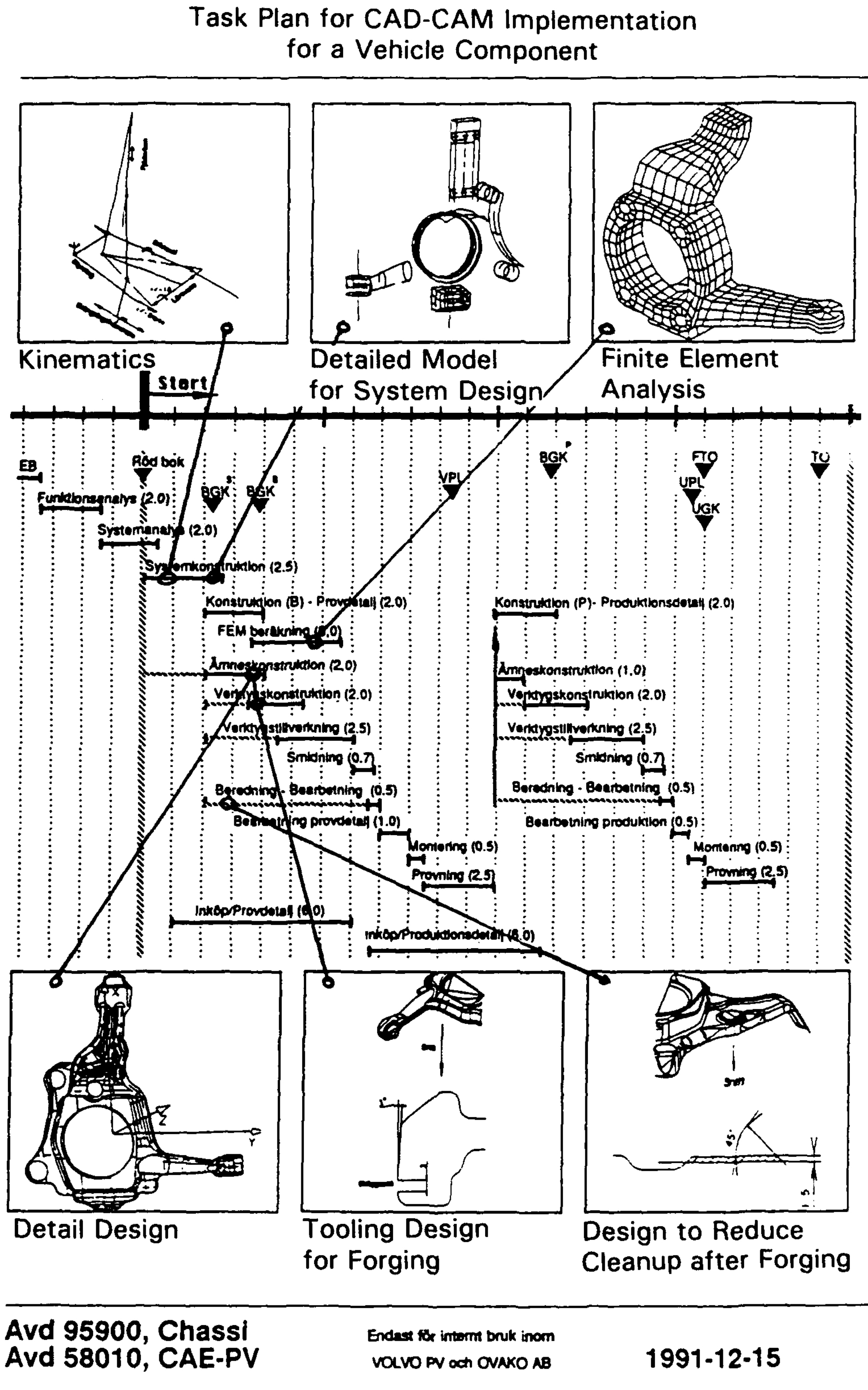

Fig. 1—New schedule for designing and prototyping a steering knuckle, showing key information and when it needed. This is a schematic schedule for the design, development, and testing of a car steering knuckle. It was prepared by the Volvo CIM team to present to its management the results of studying and drastically shortening the knuckle's design process. The schedule shows several tracks ongoing in parallel. The schematic also shows the kinds of information needed at various stages of the process. (Courtesy Volvo Car Corporation. Used by permission.)

launched a series of integrated design activities, Volkswagen (VW) is not as far along and has not unified its approaches and CAD facilities as much as Volvo has.

My host emphasized the primacy of "process" in design over the skill required to design individual items. In this sense he felt that most university design research missed the key issues. The German design process standard VDI 2221 is also too general. It lists the broad steps that must be accomplished, he says, but does not fill in enough details. VW has hired engineers skilled in design methodologies to improve the process internally. It also understands the need to improve its suppliers' design processes and integrate them with its own.

This effort is now several years old and is being carried out differently from the way CAD was originally introduced. Twenty years ago, the R&D people led this process. They felt that geometry was enough and that manufacturing input was not needed. Now a more bottom-up method is being used to define design processes. For example, a person from logistics is defining the notion of "design for shipability." Also, by law in the FRG, products will soon have to be designed for recycling, and their packaging must already be recyclable.

Volkswagen also defined "module" in an interesting way: a module is a feature of the car that helps differentiate the car in the marketplace. This is different from the way suppliers, engineers, and manufacturing people define it. It is important not to out-source the strategically important modules, those that are relied on most heavily to sell the car. This helps define core competencies that the company must retain and support with CAD and better design processes.

A major factor governing use of computers in design is the rapid growth in the amount of data required. Ten years ago, an FEM model of a car for crash analysis purposes had 1300 elements. Now it has 40,000. Part models can occupy hundreds of megabytes. Another factor being tackled by all the German car makers together is transferring all these data back and forth with their suppliers. A subset of IGES (International Graphics Exchange Standard) has been defined, called VDAIS (German Motor Manufacturers' IGES Subset). Within VDAIS, VW has set up its own standard called PASS [Product Data Standard Subset (In German: Productdaten Austauch Schnittstellen)]. Most commercial 2D and 3D modelers now conform or will soon. Although most of the standards deal with representing drawings, a few of the defined items are there because of advanced design requirements: minimum radius notation needs to be standardized in part because design for assembly (DFA) will use the information.

Volkswagen feels that the FRG is ahead in creating such standards and in holding ongoing industry-wide symposia to disseminate and improve them.

Aerospatiale

Aerospatiale[2] is one of the largest aerospace companies in Europe. It designs and accomplishes the final assembly of the Airbus family of aircraft, as well as making many of the parts. It adopted the "design-build team" concept of design process organization in 1975 and practiced that method for two years before introducing computers. This gave it the opportunity to document the new organization and information flow patterns and decide what it wanted from computers.

The result is that the computerization has been focused on integrating the design process rather than on supporting one phase, such as geometry or conceptualization. Aerospatiale originally wrote lofting software but now relies mostly on Computervision for geometric modeling. The main in-house activity has been to develop an entity-attribute type of database in which a wide variety of engineering information and process descriptions can be placed alongside the geometry. All the designers have access to this database, which was described as "an industrial plant for processing data" rather than a "storage place."

Aerospatiale notes that assembly is the next frontier in computerizing the design process. The currently available tools offer little in the way of assembly process modeling and mainly support configuration control. Another weak spot is in the design of pressed or folded parts, where CAD tools offer no process support. What is needed is better engineering knowledge of materials behavior linked directly to the operating behavior of the machines in its plants. It appears at present that

each company, or possibly each industry, must develop these tools. The CAD vendors, according to my host, do not have the expertise or the ability to divide their efforts across the needs of many customers.

The present way of designing aircraft consists of converting a preliminary design into single parts and then subassemblies. When assembly problems are discovered, the single parts must be redesigned. Aerospatiale wants to be able to validate assembly before single parts are designed, but there is a paradox in this hope: many assembly problems are caused by very small details on the parts. Checking assembly at a preliminary design stage will therefore not catch all the problems. However, major interferences, sequences, and access issues can be addressed. "You don't want to put an air conditioning duct where it might drip condensate onto a computer."

To encompass assembly properly, the database will have to be revised. Several views of parts and assemblies will be needed, including several degrees of detail and stages of subassembly. Also, a new kind of person will be needed, the assembly checker. Such a person may be needed for each main engineering system (air conditioning, for example). The subcontractors will have to be involved in this as well, and by remote access from various parts of Europe.

Comment

Predicting future problems in fabrication and assembly during concept design runs straight into the paradox cited above: small details can have big effects. This fact eliminates strategies that depend on scaling laws and forces one to track all the details down sooner or later. Thus a triage of problems must be carried out, so that those which really can be handled during concept design receive attention, while the others are left aside.

On this basis, a priority list might look as follows:

1. gross incompatibilities between assemblies in terms of function, malfunction, proximity, and so on (moisture, heat, flying parts due to engine failure, human access during normal operation, diagnosis, or repair)
2. access for routine things like original assembly or scheduled maintenance
3. access routes for interconnections between things, including approach paths to the items being connected
4. general "layering" of things: what's on the outside, what's next, etc.
5. incompatibilities or interferences between single parts.

Telemechanique

Telemechanique[3] designs, builds, sells, and uses internally a wide variety of automation equipment plus the associated controls and software. Its design research includes problems and methods in the design of multi-part electromechanical items that are made in a wide variety. How does one control the design process so that an easily made product family emerges? How does one assure high quality and low defects while switching effortlessly from one version to another in unpredictable batch sizes? What rules are needed to make sure that the design process is systematic, that the number of parts does not grow uncontrollably, and that the varieties available meet the needs of customers without strangling the manufacturer?

M. Albert Morelli, Director of Automation and Productivity at Telemechanique's R&D Laboratory, gives the example of contactors (relays that switch motors on and off): when looked at properly, a contactor is a subset, in function and parts complement, of a *reversing* contactor. To take advantage of parts commonality, the reversing contactor must be designed first, since it bears the main design constraints. Designing them in the other order (plain contactor first, since it is sold in much higher numbers) will only require it to be redesigned when the constraints are discovered.

More generally, Morelli has developed an approach to designing high variety products. It includes several steps:

1. Functional decomposition
2. Modularity
3. Definition of subassemblies
4. Reduction in apparent variety by part commonality
5. Design for automatic assembly.

Functional decomposition (conversion of functional descriptions into specific lists of parts) is a familiar step that appears in most design methodologies. It requires experience so that the functions are represented by an economical number of parts. This step is complicated when the product must be made in many varieties because some functions, and thus their respective parts, may be in some varieties but not others. Whether to make these as separate parts or merge them with their neighbors is a constant challenge. A similar challenge occurs when parts must change identity, shape, or composition at various points along the spectrum of varieties. Where along the spectrum should the transition occur? Does the change affect other parts? Which ones? etc.

An example is given below that shows how fabrication, assembly, cost, and market demand all must be taken into account. No systematic design tools for such decisions exist.

Modularity involves making up a function by combining several identical or related parts (Morelli says that modules are different from subassemblies. Modules are mainly of interest to the designer, while subassemblies are of interest to the manufacturer. They interact and must be defined carefully during design). At Telemechanique it shows up in products with repeated internal structures that implement repeated functional requirements. (*N* contacts, where *N* can be chosen by the customer, for example.) The design choice is between assembling the repeated parts or designing special parts that contain the required number of elements.

Morelli is not uncritically in favor of modularity; he recognizes its drawbacks as well as its advantages. Modularity brings flexibility but requires more parts, more careful attention to tolerances that build up when these parts are assembled, and more effort in logistics to muster those parts needed for each order. The choice is also influenced by the cost of making molds and the influence of production volume of the different types of product.

Consider the case where motor control protectors with three or four poles (contacts) must be made. Table 2 shows four different ways they might be designed. The assumption is that the cost, complexity, and design/build time for a mold for making the parts will increase with the number of poles. Each different design alternative is intended to generate both varieties of the product: If 4-pole units are low-volume sellers while 3-pole units are high-volume sellers then designs 1 and 4 are not likely to be economically viable alternatives. Designs 2 and 3 are more feasible in this case, but it is not immediately obvious which is the best.

This example shows that to design the product properly requires a good model of the market, plus the ability to predict the cost of the associated molds and the tolerance buildups in the alternative assembled units, and the ability to model the cost structure of the product as a whole: materials,

Table 2—Design Alternatives for a Multi-Module Product

Number of Poles	Design Alternative			
	Design 1	Design 2	Design 3	Design 4
3	a special 3-cavity piece	3 single-cavity modules fastened together	a special 3-cavity piece	3 single-cavity modules
4	a special 4-cavity piece	4 of the same single-cavity pieces as above	the above 3-cavity piece plus one of the single-cavity pieces	a special 4-cavity piece

logistics, fabrication, assembly, inspection, and test. Some of this information must either be in or linked to, the data model of the product. Its presence would support the module-family design process, not just describe the product.

Taking a broader view, one must be careful not to offer so many modules that the customer becomes confused. One way of selling offers the customers the chance to "design their own" by choosing from a catalog of the modules. One must understand the spectrum of needs and then construct the modules so that it is easy for the customer to see what modules to combine. Then, of course, one must be able to make and deliver them "just in time."

One must be careful not to confuse the designers either. When a large number of varieties must be encompassed and some common parts are involved in each variety, a design change in one part can cascade changes throughout the family in unpredictable ways. A strong database is needed to keep track of such interrelationships. It would need to know about related part features on different parts at a geometric level as well as about sets and relations between part families at the module level. This lends additional richness to the idea of a "product data model:" another example that contains data to support the design process, not merely to describe the product.

Siemens Dynamowerk, Berlin

This division of Siemens makes electrical generators and motors. Some are huge—more than 16m in diameter—and only a few are made each year. Midrange units are made in larger quantities and come in several types, for which a family of designs exists. The smallest units are made in relatively large numbers and a predictable modular design approach can be used, along with a lot of CAD and some numerical control. But the largest machines are always specials. They contain an enormous amount of material, which drives their cost, which in turn drives the designers to think up new shapes every time to save material. By contrast, the cost of the smaller machines is driven by labor, so the effort goes into automation. Thus three kinds of design are needed for the different size machines. "We always know the shapes of the small machines but the shapes of the larger ones are different every time," said Dr. Mario Schacht. His job focuses on the largest ones. The designers deal with only a few each year, and the need (habit?) to make up new shapes for what are in fact almost the same parts has created a hodgepodge of part names, part numbers, and data that are unusable for later designs. To improve this situation, one would think that it would be enough to get the designers to use the same names each time, or to give out predefined sets of part numbers for the different types. This in fact has now been done. But in addition. Dr. Schacht has had to restructure the entire design process so that the generic elements of the generators are known to everyone and everyone thinks of the "same generator" when they are working. This means not only that everyone working on a given generator thinks of the same one, but that this one is "the same" in basic ways as all the past ones.

To accomplish this he has had to create a sort of standard design script, conceptualizing aspects of the design that even seasoned designers had not realized. He has drawn up design trees holding information such as "every generator has a shaft; every generator has a rotor shield that is either one piece or is segmented, depending on... If the rotor shield is segmented, then part A1 is eliminated and parts A2 - A5 are used..." On the wall in the office are large sheets of paper showing this structure in detail, representing months of work.

These design scripts are very much in the spirit of the research of his former professor, Wolfgang Beitz, of the Technical University of Berlin.

PSA Peugeot-Citroèn

Andrè Rault, with a 1966 Ph.D. from Berkeley in controls, joined PSA three years ago. His goal has been to bring a more systematic approach to its design methods, especially for mechatronic components like transmissions and brake systems.[4] He has brought in software called CAMAS from the University of Twente that permits hierarchical Bond Graph models to be built. Several quite accurate models of complex items have convinced the engineers that this is a valuable method. Rault has now launched an ESPRIT project to create a library of proven Bond Graph models of common

mechatronic components, together with their geometry (a link not supported by CAMAS) so that systematic Bond Graph modeling and design of complex mechatronic things can be done more easily in industry.

CAMAS is like the original Bond Graph simulation system ENPORT in many ways. It supports hierarchical models of complex hybrid systems. In an X window one can have a model with two nodes: ENGINE and TRANSMISSION. Clicking on one of these nodes reveals a more detailed model, and clicking on its nodes reveals even more detail. At each level, the graph obeys the Bond Graph notation rules. At any level, explicit mathematical statements can be substituted in a FORTRAN-like language called SIDOPS to handle nonlinearities and other details. CAMAS automatically converts the Bond Graph model into a set of SIDOPS statements and evaluates them numerically.

CAMAS has been applied to modeling automatic transmissions. These are good examples of mechatronics because they have either hybrid or all electronic controllers as well as many gears, clutches, shafts, friction elements, and inertias; Bond Graphs are amply equipped to model such systems. The first model, while still approximate in some areas, accurately predicts that PSA's current transmissions jerk the car somewhat while shifting. A previous analysis of manual transmissions correctly identified gear backlash as their main source of noise. These successes have impressed the engineers, making further applications likely. A complete car and suspension system model is being built.

Dassault Systemes

Dassault Systemes (DS) is the developer of the 3D modeler CATIA (see "New CAD Software from Dassault Systemes: Starting to Combine Design and Engineering," *ESNIB*, this issue). CATIA started out as an aerospace industry product but recently has made major inroads in the car industry. New software plans include providing object-oriented databases, using free-form 3D sketchers, providing the ability to manipulate constraints, engineering equations, and tolerances, and modeling assembly processes. A new and quite large ESPRIT project on assembly called SCOPES has just begun, with partners Telemechanique, Cranfield Institute of Technology, the Ecole Polytechnique Federale de Lausanne, and two industrial partners. It is a turning point in CAD capabilities.

These projects are interesting in part because they represent topics that are being worked on at several university research laboratories. Either technology transfer is starting to happen very rapidly, or the universities are not very far ahead of some applications. Both may be partly true, and in some cases the universities may be behind. In others, DS's capabilities will be quite modest in these areas at first.

Apparently much of this development has been driven by the customers. "It's pretty hard to keep up with them," says Dominique Florack, Manager of R&D Strategy. Another technique for redirecting DS has been to hire people from engineering organizations, including its former parent Dassault Aircraft, so that new developments will be more focused on the needs of current and new customers. New techniques from research are obtained in part by hiring students who did the research. More recently, small research grants directly to universities are being made.

DS is also interesting in the way it develops new capabilities. According to Florack, half of their internal R&D projects are co-funded with one or more industrial partners. These partners will have a two-year exclusive opportunity to use the results before they are sold generally.

The SCOPES project, as stated above, represents a totally new direction for CAD. Assembly is the first really new CAD/CAM application since numerical control, and assembly brings totally new issues to the surface. These include:

- dealing with several parts at once;
- understanding all the ways those parts will interact;
- exploiting the integrative character of assembly to help tie the design process together; and
- understanding assembly as both a process that occurs in the factory and as a way that parts provide "engineering services" to each other (support, location, sealing, heat

transfer, fluid retention...) and then linking those "services" to the assembly constraints inherent in individual part mates (slide in, fit against, glue together, fasten with screw, compress O-ring,...). [Note: this way of looking at assembly was expressed to me separately by researchers at Leeds University.[5]]

The project, while ambitious, will not deal with all of these issues. It has three segments: off-line, on-line, and the off-line-on-line interface. In the off-line part, directed by DS, assemblies will be modeled geometrically, and feasible assembly sequences will be found. The "best" sequence will be selected and converted into an assembly process plan, from which an assembly system will be designed. In the off-line-on-line part (co-directed by DS and Telemechanique), this system will be detailed, including all the controls and sensors, and a discrete time simulation will be generated to test its operation, including failure detection and correction. In the on-line part (to be supervised by Telemechanique), the system engineering will be done, including all wiring diagrams, diagnostics, monitoring, statistical quality control, user interface, and communication networks.

DS is moving CATIA from a geometry modeler to an engineering design support system. It appears to be actively seeking recent research results. At present CATIA is still primarily geometry-oriented, and the hard engineering capabilities have only recently been considered. But this is the long-term trend, and other CAD companies are moving in the same direction. This trend should present challenges and opportunities for the research community.

Summary

The companies visited are trying to figure out how to implement Concurrent Engineering, shorten their design cycles, and manage the enormous amounts of data that are typical of their products. Uniformity of data descriptions and smooth conversion from one description to another are prime concerns.

High on companies' priority lists are stronger links between geometry, engineering, and design for business strategy. Familiar computer-aided engineering (such as finite-element calculations) is well supported by all commercial software. The companies are now interested in tolerances, design of multi-part products, design of product families, design for manufacture and assembly, prediction of costs, and generation of documentation. As they explore new CAD capabilities, the companies are discovering new kinds of applications faster than the vendors can keep up. Each vendor often has a key customer that not only drives its development but nearly saturates its programmers.

The CAD vendor visited, like its competitors, is aware of these needs and appears to be shifting the focus of its products toward supporting them and away from the industry's traditional focus on geometry. It will soon release a version of its three-dimensional modeling system that permits dimensioning and tolerancing, geometric constraints, and limited mathematical constraint management. Companies using other vendors' software indicate similar trends. In several cases, capabilities that are subjects of research at laboratories visited are now supported commercially or soon will be.

However, vendors' work mostly deals with individual parts and seeks to link the analyses specifically to their geometry. Mathematical and conceptual design are not well supported, although research and development to generate that support is going on. Users, on the other hand, are looking for more capability for handling assemblies and for supporting hard engineering. When they cannot get this from the vendors, they are trying to develop it themselves. Few companies said they found much that was useful in current university design research, and some doubted that the vendors could supply what they need either.

WHAT RESEARCHERS ARE DOING

Laboratories Visited and Their Main Activities

Table 3 lists research laboratories visited and their main activities. These laboratories differ widely in their research focus and approach, but some common threads were observed. The main focus is on individual designers dealing with various stages of the design process from concept to details. Concept efforts include helping designers focus their thinking during concept design, helping them link requirements to possible functional and

Table 3—Research Laboratories Visited

Laboratory	Main Activities	Example Visit Topic
University of London	Product design	Quality
Cranfield Institute of Technology, U.K.	CAD, CIM	AI in design, assembly modeling
Ecole Nationale Superieure des Arts et Metiers, Paris	Product concept design	Styles of Concurrent Engineering
Ecole Polytechnique Federale de Lausanne, Switzerland	Microtechnique, robotics	Design of economical assembly systems
Institut de Productique, Besancon, France	Automation and Design	Assembly planning, assembly machine design
Institut für Fahrzeugbau Wolfsburg	Education of engineers for car companies	CAD, robotics, emission testing
IPK Production Technology Center Berlin	Design, CAD, design for manufacture, automation	Feature-based design, semantic features
LAAS National Automation Laboratory, Toulouse, France	Robotics	Mobile robots for factories and planetary exploration
University of Lancaster, U.K.	Design methods for electromechanical systems	Synthesis of mechatronic systems from requirements
University of Leeds, U.K.	Design, CAD, geometric models	Product data model definition and editor
Katholieke Universiteit Leuven, Belgium	Mechanical engineering	Robot assembly, structural analysis, rapid prototyping
Technical University of Aachen, Federal Republic of Germany	Mechanical design of machine tools	Assembly-based design, expert system for spindles
Technical University of Berlin	Systematic design of electromechanical systems	Computer system for aiding concept, functional, and detail design

physical realizations, and presenting simulations of concept system behavior. Detail design efforts include creation of part designs with both geometric and semantic (nongeometric items like constraints, symmetries, comments) features, creating and analyzing complete engineered systems in a limited domain, and providing feedback on a design's suitability for manufacture or assembly.

Only one laboratory is trying to develop product data models as a separate research activity. Only one laboratory is trying to integrate aspects of design process management into its research on design of complex systems. Several laboratories are trying to apply Artificial Intelligence (AI) methods or neural nets in an effort to bring engineering knowledge into the design process. Other researchers feel that AI will be of little help.

Several laboratories are studying assembly. One is focusing on helping designers of assembly equipment; the rest are dealing with product design issues: determining assembly sequences, trying to encourage designers to conceive a product as a set of parts rather than one part at a time, and seeking to link part sets to product functions.

Only one appears to be thinking critically about concurrent engineering as a human activity, defining roles for different experts to play at different stages of the process.

The sections below are organized as follows. First, the approaches of several laboratories to the

same research area is discussed in two contexts: AI in design, and computer aids to the concept design process. Following this, several sections describe activities at individual laboratories.

Representative Research Activities of Interest

Artificial Intelligence in Design

Design seems to require so much specialized knowledge that AI methods have long been attractive as a way to improve computerized design methods.[6] Now that several years' work exists, we can ask

- can Artificial Intelligence really contribute significantly to design and, if so, in what way?
- are AI's existing methods adequate, and if not, then what improvements are needed or what other methods should be added or substituted?

One can conclude from what follows that AI is earning a place as a training aid or expert-simulator that can duplicate what good designers do now on design problems that fall in a previously defined class of a given object. However, new kinds of designs of such objects cannot be tackled. The exact limits of "new" have not been well defined. Communication between designers and knowledge engineers is weak, with the result that deep knowledge is not obtained. It is possible that the inability to get deep knowledge is a symptom of weakness in basic engineering models rather than or in addition to weakness in the methods of knowledge engineering.

Researchers do not deem existing knowledge representation schemes adequate to capture what designers do. Possible explanations include the fact that designers do not explicitly know and use rules, that their thinking processes are not strictly linear, and that they do not in fact know some basic engineering or perform necessary and feasible analyses. Instead they may copy their own or others' procedures.

AI methods may not be able to escape these limitations until they are combined with analytical methods based on first principles.

Three AI-design projects, two at Cranfield Institute of Technology in the U.K. and one at the Technische Universität Aachen, are summarized below. These are then contrasted with some design methods based on first principles of engineering mechanics and thermodynamics. Each is introduced by a quote from a researcher.

"Regarding knowledge bases and rule chaining for aiding designers, the methods are weak but the knowledge of designers is pretty shallow, so for now the methods are adequate."

This trenchant comment was gleaned from discussions at Cranfield with Dr. Jaz Saggu, associated with the College of Aeronautics. Artificial intelligence has important opportunities in aircraft design, manufacturing system design, and design for manufacture, he says.

The group's general approach is to regard AI as creating an environment that contains an array of tools useful to the designer. Some of these will be traditional AI tools; others will be traditional engineering tools. The designer should be able to apply any tool needed without being an expert in its use. Artificial intelligence should also provide a front end with an explanation facility so the designer can see why a decision or recommendation was made. The group does not develop new AI methods and is not committed to one style or approach.

Example projects they have worked on include

- critiqueing designs for manufacturability;
- preparing designs for FEM, or recommending which parts of a design should be subjected to FEM;
- structural optimization; and
- designing safety-critical software.

An important new project funded by the EC, called EDID, involves using AI methods to merge two versions of the same design and detect mismatches. Part of the AI component will be to combine two people, a rule base, and an agent to negotiate the mismatches.

The project will also generate a new kind of Interface Control Document (ICD). It will have a hierarchical structure as well as several data

classifications or views: geometry of parts, minutes of design meetings, lists of mismatches, and so on. The hierarchical tree arrangement will list the systems and subsystems of the item being designed (a communications satellite) and the subcontractors are expected to choose what to work on by making reference to this tree.

Professor Alan Morris provided a different view of this project.[7] He stressed the need to better understand how designers operate when trying to merge portions of a design and negotiate mismatches between sections designed by different people or companies. Important questions are: "What information should be provided, especially concerning the nature of a mismatch?... "Where will this information come from?" For example, suppose two pipes must be joined across an interface and they turn out to be misaligned. Simply having the computer report "mismatch" is insufficient. More likely, it must report not only the directions of mismatch but also the physical and economic freedoms available within which adjustment strategies can be found. Is either pipe flexible; will they break if they are simply pulled together during actual assembly; is there space around them to reroute them; what negotiating strategies will the different designers use?

"AI-design folks think they are in the home stretch providing tools for design."

This equally trenchant remark came from Mr. Graham Jared, an engineering-oriented researcher in the School of Industrial and Manufacturing Science at Cranfield who is studying design for assembly by using both AI and other approaches.

Jared apparently bases his opinion of AI in design in part on his experience trying to build rule-based Design for Assembly (DFA). The project is an outgrowth of work by Prof. Ken Swift of the University of Hull and Lucas Engineering, a large mechanical engineering company. Swift built a software-based DFA system similar to the famous one made by Prof. Boothroyd. Both systems ask the designer a series of questions about each part in a product design (is the part easy to pick up; is it symmetric—thus easy to feed automatically to a robot—and so on). From the answers, the computer computes a score that predicts how long assembly will take or indicates whether the part should be redesigned to make assembly easier. The software can also detect the opportunity to make two adjacent parts into one.

Swift found, to his and Lucas' disappointment, that the computerized system did not create results any faster or better than answering the questions with pencil and paper, a result that others have also found. The method also seemed incapable of helping design really new things or of handling situations not anticipated when the questions or scoring methods were developed. Finally, they found that the users did not really understand the questions and often answered optimistically when asked to judge ease of assembly.

So Jared and Swift determined to automate or assist the DFA evaluation process, and for this they needed a geometric model and a set of rules and AI methods for doing the evaluation. Some of the required information can be located and identified as features, as long as these are identified in some way. For example, chamfers (bevels) around the rims of holes are known to make peg-hole assembly easier. Checking for the existence of chamfers can be easy if the CAD data are properly organized.[8]

It turns out, however, that they knew only some of the features that would be the "knowledge-carriers" relevant to DFA evaluation. Only some of these are geometric. Other kinds of relevant information do not show up in CAD databases: smoothness of surfaces or likelihood that there will be oil on the surface during assembly (both fundamental to ease of assembly of rubber seals, for example, or to the likelihood that a person might drop the part); amount of resistance force that might oppose assembly (such as in spring-loaded parts); and so on. They stress the amount of "lore" that they must get out of the designers.

In addition, there is a built-in conflict in using CAD as the source of the data for the evaluation: companies would rather have the evaluation done on a concept, not on a fully developed CAD model. Such models take a long time to build and can be hard to revise. No way out of this conflict has been devised. You cannot do geometric reasoning without some geometry or a workable representation of the geometry that contains the necessary information. Defining "necessary information" is the challenge, since some of what we now deduce

from geometry might be expressed another way if we knew what it was and how it would be used. An example is the mutual direction of assembly of two parts. This can be deduced by geometric reasoning about the shapes of the mating surfaces. Alternately, the designer can create mating surfaces by picking them out of feature libraries as data objects (pegs, holes, slots, chamfered holes...). These objects can contain the mating direction as a numerical/text attribute.

So the question is not just whether AI methods can help, but also what information must be available before AI methods can contribute to their best advantage. Consider part count reduction. The current method of detecting the opportunity to eliminate parts operates by having the designer answer three questions about adjoining part pairs:

- are the parts made of the same material?
- is the method used to join them permanent?
- is there some important reason why it should be possible to separate them after assembly?

If the answers are YES, YES, NO, then the two parts should be considered for consolidation into one. The first two questions can be easily answered from properly structured and augmented CAD data. The third one, however, requires real knowledge: it concerns the product's function, intended use, failure modes, repair methods, modularity, and so on. The third question is, in fact, the only really interesting question, and it is more than just difficult to answer. Like the question of how to choose tolerances, the required knowledge can be said to reflect the entire design process. It is not general knowledge but rather specific information about the product. Is it reasonable to expect future product data models to contain such information, even if designers rather than algorithms make the decisions about how to use it?

"When we tried to determine the designers' rules for machine tool spindles, we found that there were far too many for an efficient rulebase. The designers could not verbalize many of them. Also, many steps in design do not seem to follow a logical path. So we turned to neural nets instead to capture what the designers were doing."

This comment is an evaluation of the limits of AI methods and indicates a novel use for neural nets as a substitute. It was made by Mr. Baer, a Dr.-ing. candidate at the Technische Universität Aachen. He is building an aid for designers of machine tool spindles. The design system being developed covers basic requirements, types of machining it will do, geometry, choice and placement of bearings, stress analysis, and design evaluation and redesign. The neural net has been built for the evaluation and redesign phase. So far, its performance cannot be judged successful.

Several more conventional AI techniques suffice to aid parts of the design process. Rulebases are used to hold information about the amount of friction or types of failure modes of different lubrication methods (grease is stiff and can dry out, but it takes high loads). Design requirements are expressed as fuzzy categories like "the load is high but the speed is low." A set of precalculated decision tables is used to combine the requirements and the rules and presents the designer with a prioritized set of solutions from which to choose. "Duplex greased roller bearings are the first choice. Their cost is *X*."

To aid generation of spindle geometry, many spindle designs were studied, and characteristic regions were identified: the tool mount end, the step-down from the tool mount to the first bearing region, and so on. Each region can have a variety of shapes, which are modeled with adjustable parameters. A geometry description language was developed to generate these regions and hook them together. An example statement in this language is "The step is on the same axis as the mount and the first bearing region." A rulebase looks at this description and the requirements and tries to find what type of region should be picked from the available ones. The designer can substitute his own choices if he does not like the computer's.

Evaluation is the step that could not be captured by rules. Two large neural nets are being tried instead. One creates an evaluation while the other suggests design changes. Many designs were studied, and designers' revisions of them were recorded. These before-after pairs were used to train the net.

This large and ambitious neural net is still under development. Recurring issues are how many hidden layers to use and how many neurons to put in each layer. Too few layers or neurons will cause the net to fail to capture the desired

nuances, while too many will cause the training session to fail to converge. Neural nets are rare in design software, so not much experience is available.

Taken as a whole, the spindle design aid has occupied Mr. Baer and others for four years. He says it can do well on types of spindles it has "seen" before but not for ones that are new. Variants of standard types are the easiest. It is a great training aid, and it permits a student to design an acceptable spindle in about a day. An experienced designer takes an hour, while a designer with 20 years' experience can design a better spindle without the computer.

Comments

Expert systems appear to be primarily empirical. They are often applied when the developers conclude that there is no hope of an analytical solution. A classic case is that of medical diagnosis: the resulting expert system is a model of the doctor, not a model of the sick person. Many expert systems hoping to capture design are similar.

There is no doubt that systematic attempts to model processes bring large rewards. Asking doctors to think about their diagnostic methods revealed an underlying structure that had not been taught explicitly in medical school. Companies have learned that modeling design processes reveals important opportunities for improvement.

But is it worth reconsidering the conclusion that spindle designs, for example, cannot be evaluated analytically. What we can tell is that the designers who were questioned did not use analytical methods. This in itself is not really sufficient proof that an analysis is impossible, but only that one has not been attempted, or has not been pursued with enough vigor, or that the designers questioned were not aware of existing or potential analyses. Too much reliance on expert systems puts off the day when better understanding of the underlying phenomena must be obtained.

Expert systems at least have the positive feature that one can read their rules and perhaps even learn something from them. By contrast, a neural net is completely numerical and empirical. No one knows how to "read" them. They represent the ultimate in avoiding better understanding of the engineering.

A counterpoint to AI in design is provided by researchers studying design methodology. Examples include Professor Beitz' systematic design (see below) and Professor Suh's design axiomatics. Here I would like to discuss the work of Prof. Michael French of Lancaster University in the U.K. In a recent book,[9] he uses a series of examples and first principles in mechanics to bring out a number of considerations that designers often use implicitly. He says that these can be made explicit and, in line with the above argument, can be dealt with analytically.

Examples of these design considerations are:

- *Disposition* - the essence of many design problems is to identify a key commodity, such as space or energy, whose allocation dominates the problem. Once the commodity has been identified, the allocation can often be made analytically.

- *Combination or Separation of Functions* - it is often efficient in terms of space or weight to make one item perform several functions. A classic counter-example is James Watt's invention of the separate condenser for steam engines. Prior designs used the piston cylinder as the condenser, making it too hot to be efficient as a condenser and too cold to be efficient as a driving element. A thermodynamic analysis was not available to Watt but one can be done and the advantage of making the separation can be calculated.

- *Structural Efficiency* - J.C. Maxwell proved that the integral of force times distance over a stressed elastic structure depends only on the pattern of applied loads, not on the geometry of the structure. French calls this integral "pertinacity." Efficient structures have minimum pertinacity, and the designer obtains it generally by maximizing the tensile loads and minimizing the compressive loads inside the structure. Minimizing the pertinacity will reduce the amount of material required to support a given set of loads. The designer will try to reduce the material

until every element is stressed to its safe limit. By using first principles, French shows that efficient structures are also stiffer than inefficient ones.

French says in the book's preface that it is likely that good designers create efficient structures but it is not obvious that they are aware of pertinacity or that they calculate it explicitly. My questions are: If they do not use pertinacity, what do their "rules" for designing structures look like? Could something like pertinacity be deduced from their designs? Is that the right way to discover pertinacity?

Conclusions

AI methods obviously have a lot to contribute to design. The limitations of AI acting alone are becoming clear, however. It assumes a type of thinking process that designers may not use, or may not use exclusively. Designers may not have clear enough or analytical enough views of their work to make rule-based or neural net methods efficient or to permit these methods to be innovative in a meaningful way.

For the time being, fruitful approaches appear to combine all of the methods we know of: rules, mathematical and geometric models, extended data models, object-oriented descriptions, calculations, numerical searches, and so on. Only a few laboratories are pursuing such a combined strategy and none is using a large number of methods together.

Converting Functional Specifications to Concept Designs

Most commercial computer-aided design (CAD) is not really design software. Instead, it either supports two-dimensional drafting or three-dimensional geometric modeling, with added text representing dimensions, tolerances, process notes, and so on.[10] The most advanced commercial CAD software permits geometry to be parameterized by numerical or symbolic arguments, with some equality and inequality constraints on these variables. However, such software mainly supports creation of geometry at a detailed level; it does not directly permit engineering, exploration of rough concepts, or discovery of conflicts and tradeoffs.

Researchers have taken note of these gaps and are trying to create CAD that will help designers explore nongeometric concepts and create rough realizations from loosely stated design goals and required functions. Their approaches include one or more of the following:

- scripts or design procedures that guide the designer from the specifications to classes of realizations in terms of known elements;
- diagramming methods that permit the designer to hook elements together in different data views;
- engineering-oriented approaches that permit the designer to think functionally about groups of predetermined elements, with the computer providing some engineering knowledge or constraints.

A summary sense of the state of these efforts can be gained from the following generic anecdote. Each of these research groups showed me points in their software at which a conversion was made between a more abstract representation and a more concrete one (from the statement "convert energy" to a diagram of a motor-generator set, for example). In every case, when I asked "Did the computer do that or did the designer?" the answer was "The designer."

I believe the fair thing to say at this time is that concept design research software can be characterized as "inspired sketch pads," capable of generating and searching structured lists, constructing graphs that connect elements in various ways, or accessing rules or tables to help evaluate performance of elements. Good graphical user interfaces are being developed to support these activities. But little has been done so far to exploit the structures thus created in a systematic way, such as checking for correctness and completeness. Nor has anyone taken the obvious step of converting a correctly constructed graph into any existing systematic dynamic simulation modeling method such as Bond Graphs, although most say they plan to do so.

Behind all of the research projects reported on here is the assumption that "product design" consists more or less of a set of steps that one engages in and passes through successively, while establishing and refining information. This relatively clean view contrasts sharply with what many in industry

actually experience: superimposed on (and often dominating) this set of steps, there occurs sharp conflict, wide gaps between specifications and possible realizations, and a constant struggle to predict future problems and costs, understand the needs of other designers, and so on. No laboratory visited or known to me represents design as a struggle to identify and resolve conflicts or bases its research on such a view. Yet this view describes real design better than existing research or teaching paradigms and implies great needs for computer aids of a type that no one is trying to create.

The bottom line is that except for focused situations, which essentially constitute redesign of an existing item by using the same kinds of fairly simple elements, there is not very much progress on systems that really aid the designer, other than bookkeeping, lookup of rules, and domain-specific calculations. The reasons for this situation may be lack of basic engineering knowledge that can link form and function, lack of a mature concept of a product data model, and/or lack of a mature concept of the "product design process."

Technische Universität Aachen

Machine System Design

This project is being carried out by Mr. Repetzky, a Dr.-ing. candidate, who calls it CAE of the future. The goal is to integrate all of the tools a designer needs for designing a complex machine (CAD, dynamics, simulation, FEM, machine elements like gears and bearings, hydraulics, controls, and so on). A major goal is to combine the different kinds of data that a designer would need to attack such a problem and store the data in a unified representation.

The project is an outgrowth of the general problem of putting functional design capability into conventional CAD. His view of function in machine system design is that each machine element responds to inputs and delivers outputs. So his first efforts have gone into defining data objects for the elements and placing calculations (methods) into the objects that define the input-output relationships. A major problem for him is to decide when he has described an element in enough detail. For helical gears, for example, must he include the helix angle?

The software at present supports a mouse-menu interface that permits the designer to extract objects from a library, put icons for them on the screen, and hook them together. The elements have the required hooks on them already, and a design is not complete until all the hooks have been connected to something. For example, a drive motor has a hook for fastening it to the ground and another hook for fastening it to a rotating shaft on another element. The hooks are each responsible for fixing one or more degrees of freedom (DOF), and the software will eventually be able to tell if all DOFs have been accounted for.

If he hooks together a motor, a shaft, some bearings, a gear reducer, and a load, he can calculate the shaft torques on both sides of the gearbox. He could add tooth load calculations to the gear object but has not done so yet.

He has considered using Bond Graphs as a way to link these hookups to simulation, but has not done so. Bond Graphs trivially calculate the above-mentioned torques; in addition, they are designed to model hybrid systems, such as electro-hydraulic systems, by using the same symbols and math throughout. More fundamental, the Bond Graph method contains a number of internal consistency checks that prevent some kinds of basic modeling errors, such as failing to conserve energy or attempting to define both the force on, and the velocity of, a moving object.

Combining the consistency checks of Bond Graphs with the DOF accounting he now plans would give his system some capability for evaluating the correctness and completeness of a model. I think this would be an important property for a modeling system to have. No researcher I have visited has given this kind of thing high priority. In some cases, the designer can draw what he wants and the computer will try to model it.

Assembly-Oriented Design

Mr. Baumann, another Dr.-ing. candidate, described a system called DEMOS, on which he and others have been working for many years. It supports design of mechanical items and has several objectives. First, it seeks to bring assembly

issues to the concept design phase. To do this, it permits the designer to describe the product in terms of graphs that link parts whose geometry has not been specified. Second, it allows the designer to study the design and improve its assembleability. This, however, is done after geometry is defined.[11]

The system's strongest features deal with development of two data structures: the function structure and the assembly structure. The designer inputs both of these and the software supports the process by keeping track of all the parts, logging the designer's choices for connection or assembly methods that link parts, later accepting the shape of each part, and finally performing Design for Assembly (DFA) analyses. By ordering the process this way, Baumann hopes to encourage assembly-oriented thinking by the designer before the geometry is completely described, even though the last steps require geometry. The sequence also adheres to the German design standard VDI 2221.

Both the function structure and the assembly structure are hierarchical graphs in which nodes are single parts or subassemblies, while links indicate some kind of relationship. In some cases, the relationship is that of assembly. In others, it represents some functional aspect of the design. The functional graph and assembly graph of a gearbox are shown in Fig. 2.

Once the assembly structure has been drawn up, the system attempts to generate an assembly sequence. To do this without knowing much geometric data, the system uses several heuristics. For example, the part with the most connections to it is selected as the "base part" onto which others are added. (The upper housing or lower housing would be chosen in this example.) Parts with lots of connections to each other are candidate subassemblies.

When the assembly structure and assembly sequence are determined, the designer can assign types of part mates to the assembly links. Library features like bearing seats can be called forth, including dimensions if the designer wishes. Last, the designer uses the CAD module to make up the actual shapes of the parts that contain these part mates. When the system has all the geometry and assembly structure information, it carries out a DFA analysis and suggests places where part count can be reduced. Tables from the Boothroyd method are used for this purpose.

The assembly sequence strategies used by the DEMOS software raise some interesting questions. For example, it is not obvious that maximizing the number of subassemblies is always a good idea. The reasons for doing or not doing this may depend on information from marketing or assembly machine experts, for example. Some of the considerations are discussed in the section on Telemechanique, where product modularity is the driving consideration.

A larger issue is whether significant design decisions can be made without having defined specific geometry. Assembly decisions illustrate the question here, but it comes up in many other

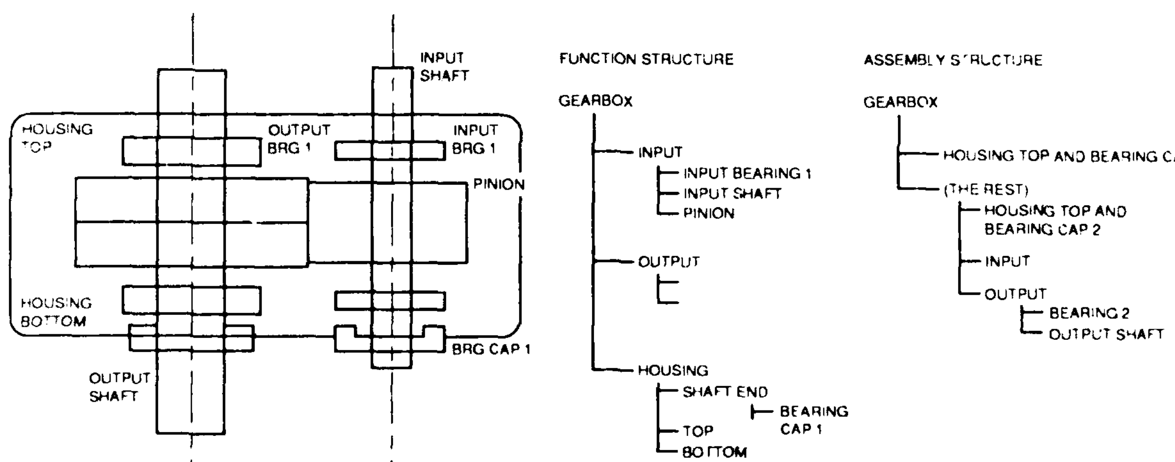

Fig. 2. Function and assembly structure of a simple gearbox

contexts. DEMOS is a bold effort to create an environment where decisions can be made without geometry. At present, however, it seems to me that many of those decisions are destined to be revised later.

The next question is whether the design is better anyway, even if the decisions were redone, just because the designer had to think about assembly much earlier than would normally be the case. No one is thinking about design processes this way: revisions are usually thought of as a sign of waste or inefficiency in the process.

University of Lancaster, U.K.

Two projects (described below) are funded by the U.K. government under the Engineering Design Centre (EDC) program. Professor Michael French's EDC project is aimed at mechatronic design, that is, design of mechanical systems that contain computation, measurement, and control as well as familiar kinematics, dynamics, fluids, strength of materials, and so on.

Schemebuilder

Schemebuilder is like Mr. Repetzky's system in many respects, with similar aims but perhaps a more analytical underpinning. It is written entirely in the commercial expert system shell KEE. There are two windows: a "building site" and a "model library." The building site is like Repetzky's hookup window and functions in basically the same way. The example here is mechatronic, in keeping with the theme of the Centre: an autopilot for a yacht. A compass provides a control setpoint for a servomechanism that will drive the boat's tiller to correct a heading error.

Two kinds of elements can be called forth, those capable of transmitting power, and those dealing only with signals. These can be joined in ways similar to those provided by Bond Graphs, including keeping track of causality. But the full force of Bond Graphs has not been utilized in the sense that no generic components (inertia, compliance) have been defined. Instead, each element represents an individual physical type of thing (tiller with rotational inertia, boat with translational inertia...).

Design begins by calling forth specific elements, such as the yacht's tiller. These elements are described only qualitatively, such as noting that the water will exert a force on the tiller in one direction while the steering motor will exert a force the other way. The motor will act through an Acme screw, whose function is described qualitatively as converting rotational input into translational output. Quantitative descriptions will be added later in the project.

Each element has hooks that permit restricted kinds of connections to be made. A browser is available in the model library that helps the designer find suitable elements for a given hook type. For example, to provide translational power for the tiller, the list could include electric or hydraulic actuators but would not include things that are not capable of driving a load.

Several extensions of the current system are planned. One deals with design concepts like function and advice/warnings to the designer. The other deals with linking the concept to a CAD system so that space can be allocated for each of the components as it is placed in the building site.

Professor French does not feel that the warnings and advice feature should be based on making the software understand engineering fundamentals. He feels that would be appropriate for design of really new things, whereas here he is dealing with hookups of already designed and understood things. Instead he would like to link the advice and warnings to a more sophisticated formulation of function. He uses the term "function structure" to describe statements of functions, perhaps at a semantic level, to which the system would respond with solution types built of library components that match the description. Once a pattern of solutions begins to emerge for a given problem, the advice might draw on the existing design. For example, if the designer has selected some hydraulic components, the system might suggest more hydraulic components to exploit the hydraulic power supply that is already required.

System for Improving Mechanical Assembly Design

This piece of software is a model editor for assembling cylindrical things with a single rotational axis of symmetry. It is a deceptively simple

context and a brilliant one because its simplicity forces certain basic issues into sharp focus while keeping side issues from clouding the discussion.

One type of assembly is involved, namely placing gears, turbines, bearings, spacers, and their required fasteners onto stepped shafts. The designer must create the stepped shape and indicate the steps onto which the parts will rest. Each set of parts, starting from a step and proceeding along the shaft through bearings and spacers to a fastener, is called a "stack." The system has been programmed to recognize stacks and to understand some of their inherent constraints. For example, a stack with no fastener is incomplete.

The system understands several geometric facts about such assemblies. For example, it can recognize stacked stacks: a step followed by a bearing, a spacer, another bearing, another spacer, and finally the fastener. It can also recognize the opportunity to create a stacked stack out of two serial stacks by responding to the command "Reduce number of fasteners." Finally, it knows when assembly is impossible because a step is too high to permit a bearing to pass over it on the way to another step. This error can occur if the system discovers that a step is too short to support the bearing assigned to it, and attempts to make the step higher.

However, the system is not aware of some basic engineering facts. For example, it does not really understand the concept of load path, that is, the idea that the fastener is going to push the spacer against the bearing, which will in turn push against the step, trapping the bearing with a compressive force. At present, when the designer places a bearing near a step the system will not place the bearing against it in anticipation of the direction the force will ultimately point. Instead, the designer must move the bearing with the mouse until it coincides with the step visually on the screen.

An extension of this idea is to recognize when axial forces must be resisted. Helical gears generate such forces. In such cases a load path to a fastener or step is needed, and the design is incomplete until this path is provided. All such paths comprise loops through the structure, with alternating loop segments in tension and compression—all adding up to zero net force around the loop. This is another case where "correctness and completeness" could be checked systematically.

The potential benefit of adding it to the system is that this provides an opportunity to study in a simple but nontrivial context the question of how to link geometric design to real engineering (elements cause loads that have to be supported by using steps and fasteners). It would be very satisfying to see a system of this type developed as a counter-example to other research where such physical facts are deduced as "rules" used by designers.

Institut für Maschinenkonstruktion, Technische Universität Berlin (TUB)

Professor Wolfgang Beitz is just coming to the end of a 10-year government-funded project to computerize the systematic design methods outlined in the well-known book co-authored with Professor Pahl.[12] The earlier years of the systematic design project included developing design methodologies for many typical engineering systems, such as pumps, transmissions, and motors. About two dozen Ph.D. theses contain this evolution. In addition, his work has developed the systematic approach and transferred it to the German standard VDI 2221, which he and Professor Pahl helped to write. This standard describes a step-by-step procedure for designing things to meet specifications. More recently the work has turned toward software.

The software is intended to consist of an end-to-end design system for converting a set of requirements into a detailed design. It has been put together around an example problem, an emergency power unit. Another example is being worked up. The software consists of modules that someday will communicate with each other, comprising a solid modeler (CATIA), a user interface, several knowledge bases, some calculations, and several browsers. In its present state, the software is preliminary and is not completely integrated. Many desirable capabilities, such as linking one stage of systematic design to the next, have not been completed. All other research laboratories that I visited where similar efforts were under way have taken basically the same approach to this most difficult problem: the software basically acts as an

aid to the designer, who must make the important transitions himself.

The software consists of a series of modules that are used one at a time, apparently unidirectionally from the beginning. At the beginning is a program that permits requirements to be listed as text with modifiers and keywords. ("Provide backup energy source." "Convert energy from one form to another." And so on.) One can browse this list, searching for repetitions of the keywords in this or other task lists from other problems. A more structured final requirements list can be made up from this rather unstructured beginning.

The next stage is a product structure, consisting of elements that receive, process, and pass along such things as force, energy, structural stability, and so on. These elements are represented as symbols and are linked to each other. (Energy flowing out of one element can flow into another, for example.) In the future, this will be the basis for a functional simulation, but right now it seems to be a graphical display. This structure can be used as the basis for a search through a database for similar structures in past designs, or one of the blocks can be expanded into a substructure of similar elements.

The next stage provides ways to link the combined requirements list and product structure to possible ways of realizing the product. I believe that there is no automatic way of creating this new list from the old one; the designer does it. Again, the computer shows symbols representing physical items like bearings, gears, shaft couplings, and so on. Beneath each of these is a knowledge base (KB) describing its rules.

One of these KB's has been extensively developed, that for connecting shafts to hubs. A VDI for this has been implemented in the software. It gives rules for sizing shaft and hub diameters for shrink fit assembly, for example, including recommended tolerances. The recommendations are based on a detailed calculation that takes into account tolerances, friction coefficient, and safety factor. However, if the designer chooses tolerances that do not agree with those recommended, he must search manually for a consistent set. There is no automatic search support.

Another level of this software is the design management system. Here a chief designer is assumed, who works from the functional requirements and product structure. This chief designer deals out tasks to other designers, utilizing the concept of a "function carrier" (FC). Ideally, the FC is a conceptual link between the desired function and a physical realization; in some cases it is an easy-to-identify thing like a bearing (carries the function of supporting the shaft). I did not get a clear impression of any other way to make this link. This gave me the feeling that this approach is useful for the "catalog component" method of design, but not for approaches that require several functions from the same item or cases where new items with unusual functions must be made up.

If this project were to obtain follow-on funding, there is the potential for a significant result, namely a system that would show how to link functional, physical, geometric, and management aspects of a complex design process into an integrated activity governed by a standardized approach. No other laboratory with similar objectives visited on this tour has made any attempt to integrate design management with design engineering the way this project has.

Comments

After reviewing the above projects, it is tempting to ask why all this seems to be so difficult. One researcher I visited spoke wistfully of gate synthesis in electronic logic. This was a "done deal" at least two decades ago. Algorithms exist that will convert a given Boolean algebra or truth table representation of a desired logic function into the minimum number of logic gates and their required hookup. Why is this possible?

There may be a good mathematical answer to this question, but I do not know it. This researcher and I surmised that logic gates have certain basic properties that mechanical elements just do not have, and these make the difference:

- each gate is discrete;
- the gates do not back-load each other but instead behave as a one-way logical cascade;
- a gate's behavior is dominated by logic; any physical behavior (heat, thermal expansion) is secondary to its behavior and does not affect it except catastrophically); and
- each gate does exactly one thing, does it

purely with no side effects, and does it so repeatably that tolerances are not an issue.

Typical mechanical and mechatronic elements simply do not have these simple properties.

Conclusions

Each of the projects described above is attempting to tackle a genuinely difficult problem, one that often has been left to "creativity" and deemed too unstructured for systematic attack and computer aids. In spite of impressive progress in restricted design domains, the problem appears to be living up to its reputation. There may be some underlying reasons for this.

The most likely one is that the problem is indeed too difficult because reducing requirements to a concept requires too much knowledge; furthermore that knowledge is not well structured.

Thus I return to the theme of the previous section on Artificial Intelligence in Design: the weakness in current approaches is due at least in part to insufficient understanding of the underlying engineering facts or insufficient effort to model them (the load paths in this section, or the machine tool spindle in the previous one—also involving load paths). The designers are probably the wrong people to ask; their approaches are too intuitive. In the near term, it may not help to continue trying to build design aids by using graphical interfaces, word searches, rule bases, or neural nets because they stand on a weak foundation in the engineering fundamentals.

Berlin Production Technology Center

The Berlin Production Technology Center combines the Fraunhofer Institute for Production Systems Technology (IPK) with the Institute for Machine Tool and Manufacturing Technology (IWF), which was founded by Kaiser Wilhelm II in 1904. It is divided into the following departments, with some of the professors holding dual appointments:

Fraunhofer Institute for Production Technology (IPK)
- Robot Systems - (formerly Prof. Gerard Duelen, now retired but not yet replaced)
- Design Technology - Prof. Krause
- System Planning - Dr. Kai Mertins
- Process Technology - Dr. Wolfgang Adam
- Computer Engineering for Machine Tools - Dr. August Pothast
- Service Technology - Prof. Spur (education and knowledge engineering)

Institute for Machine Tool and Manufacturing Technology (IWF)
- Machine Tools - Prof. Spur
- Manufacturing Technology - Prof. Spur
- Assembly Technology - Prof. Gunther Seliger
- Industrial Information Technology - Prof. Krause
- Control Technology - Prof. Duelen
- Quality Science - Prof. Gerd Kamiske

Professor Krause deals with design, especially computer-aided design (CAD), a field he has pursued throughout his entire 25-year career. His department has 40 full-time staff members and many Technische Universität Berlin [Technical University of Berlin (TUB)] research assistants. There are four activities:

1. *Design systematics* - (NOT what Prof. Beitz does, although Beitz uses exactly the same title.) The goal here is to enhance the use of existing CAD tools as well as to speed up the creation of new ones.

2. *Systems ergonomics* - This group works on scanning existing drawings and interpreting the results.

3. *Geometric modeling* - His goal here is very broad and ambitious, namely to build up feature-based design so that it encompasses feature modeling, product performance simulation, and physical modeling

(finite elements, for example). The goal is to create a complete product model so that the same data can be used for all these activities.

Professor Krause has been careful to define two kinds of features, the traditional form features and the non-form ones that he calls semantic features. He separated these two in order to confront the PDES/STEP community, which he says recognizes only the traditional kind. A nice example of a semantic feature is "*X* number of something arranged equally spaced in a circle of radius *Y*." Another is a "centering or pilot hole," which automatically will be positioned symmetrically once the designer has indicated what surface to place it in. A third is any kind of technology description or constraint, such as a surface roughness or the fact that a certain boundary must not be pierced or broken by any other feature.

4. *Technology planning* - This means deciding how to make something, including equipment selection and process planning. He has had a hard time convincing others that this is really part of design. "It simulates manufacturing, so how better to know if design for manufacture has been achieved?" He feels that some companies are ahead intellectually since technology planning has been taken over by the product design department. (I found the Japanese of two minds on this; some favor integration in one department or even in one person while others want separate departments. Companies in faster-moving technologies like video cameras wanted the former, thinking it might save time. Companies in slower-moving technologies like cars favored the latter, noting that car manufacture takes a great deal of special knowledge.)

The topics he works on include FMS (flexible manufacturing system) design, laser cutting, fixture and clamping design, scheduling, and tool management. Interestingly, he says that expert systems and knowledge bases seem to be more necessary here than in design because every process and every product is different. There is a tight coupling between processes, tools, machines, and products, and only people have all the knowledge, which they get from shop floor experience.

Software Being Developed

The most interesting software is the feature-based design system mentioned above. It contains a feature-definition language that permits designers to make their own. The research engineer is just starting to address some important issues. One is how to tell the computer where the feature should be located. He is considering using geometric placement notation like "parallel" or "normal" to other surfaces or features. Another is tolerances, which he will root in these constraints. He can say "parallel" but he has no way to check if the designer or the computer achieved parallel. Third is parametric feature descriptions. There is as yet no integration between these parameters and the ACIS geometry engine. He agrees that a way needs to be found to chain parametric constraints and dependencies in technically sound ways, but none exists yet. That is, if one is not careful, one will get spaghetti code in the form of dependency chains that have unpredictable interconnections. I believe that some other researchers are using expert systems and truth maintenance in an effort to keep track of such inference chains. Another way to achieve consistency is to bring more basic engineering rigor to the design process.

It is important to note that Dassault Systemes (see discussion of Dassault above and "New CAD Software from Dassault Systemes: Starting to Combine Design and Engineering," *ESNIB*, this issue) is already prototyping software that addresses some of the issues that this research engineer is just starting on. This is one of several cases where industry may be ahead in this field.

University of Leeds, U.K.

The Computer Aided Engineering Unit in the Mechanical Engineering Department at Leeds University, led by Prof. Alan de Pennington, has built its expertise on increasingly sophisticated geometric modelers over the last 15 years. From this base, two main trends have emerged. The

first is increased sensitivity to the need for structured data to represent products as a whole, not just their geometry. The second is a broadening view of design beyond creation of geometry to include concurrent engineering. In both cases, the Unit has established strong ties with the Computer Science Department and has also hired individual staff who combine engineering and computer science backgrounds. These ties give the Unit's research a quite different character from that of most other CAD/CAE laboratories, especially the German ones. Most research has industrial partners. The test cases they provide are "really challenging."

Some results from this laboratory have had practical consequences. One is an institute devoted to standardizing data formats and promoting data interchange. The other is active participation in the PDES/STEP process; a member of the Unit is the editor of STEP Part 41, which is a top-level document defining product configuration data.

Recent research has focused on a product data editor. This is an interactive software tool for designing product data descriptions. The implication is that product data represent a generic need but each product will require its own structure. An important issue is how to define the appropriate structure in each case. Right now, the editor creates essentially elaborated, hierarchical parts lists with links to important design algorithms and references to relevant data. The structures contain information about single parts but no information about assembly or other technical interrelations between parts other than set membership. STEP Part 41 has the same character.

New research with U.K. government and industry funding is dealing with defining product data models that will support concurrent engineering. Both fabrication and assembly will have to be dealt with. Questions to be addressed include:

- What is a specification for a product?
- What is an assembly data model?
- What is a manufacturing model?
- How can conflicts between specialists on concurrent engineering teams be resolved?
- How can different specialists' models be harmonized?

The work is just starting and no definitive results are available.

The Product Data Editor

"Product data model" is new terminology since the mid 1980s. Although the Unit's appreciation for such data goes well beyond geometry, in practice the research deals mostly with geometry. Its product data model organizes geometric data, provides a hierarchy for it, and provides hooks for applications that will work on it. Typical applications check for intersections between solids, define or check relationships between entities (parallel to...), and plan numerical control machining.

The goal of the product data editor is to permit creation of organized and coordinated data structures that allow the applications to get the information they need from one central database. This contrasts with current commercial capabilities in which data are created and structured during the design process by the CAD software. The data must often be massaged or converted to a new form before a new application can work on it.

While recent object-oriented data structure efforts have produced hierarchical trees, the Leeds structure editor creates directed graphs. In order to support recursive structures like {products contain parts or subassemblies which contain parts or subassemblies}, the graphs can be cyclic. They thus can support a "part" that is actually an assembly of parts.

I was shown the proposed general structure (Fig. 3). Interestingly, it contains "FEA analysis" as one of a collection (COL) of nodes fairly near the top of the hierarchy, indicating that a finite element model was presumably needed at the "product" level. This is quite unusual (note in this figure the repeated patterns enclosed in the shaded contours and the repeated occurrences of FEA analysis at the "assembly" and "component" level).

It is necessary to point out that this structure was carefully made, not arbitrary, but it did not represent a tested model of a real product. Yet the inclusion of the FEA node at this unexpected place provides an irresistible opportunity to ask where such structures might come from in the future. All

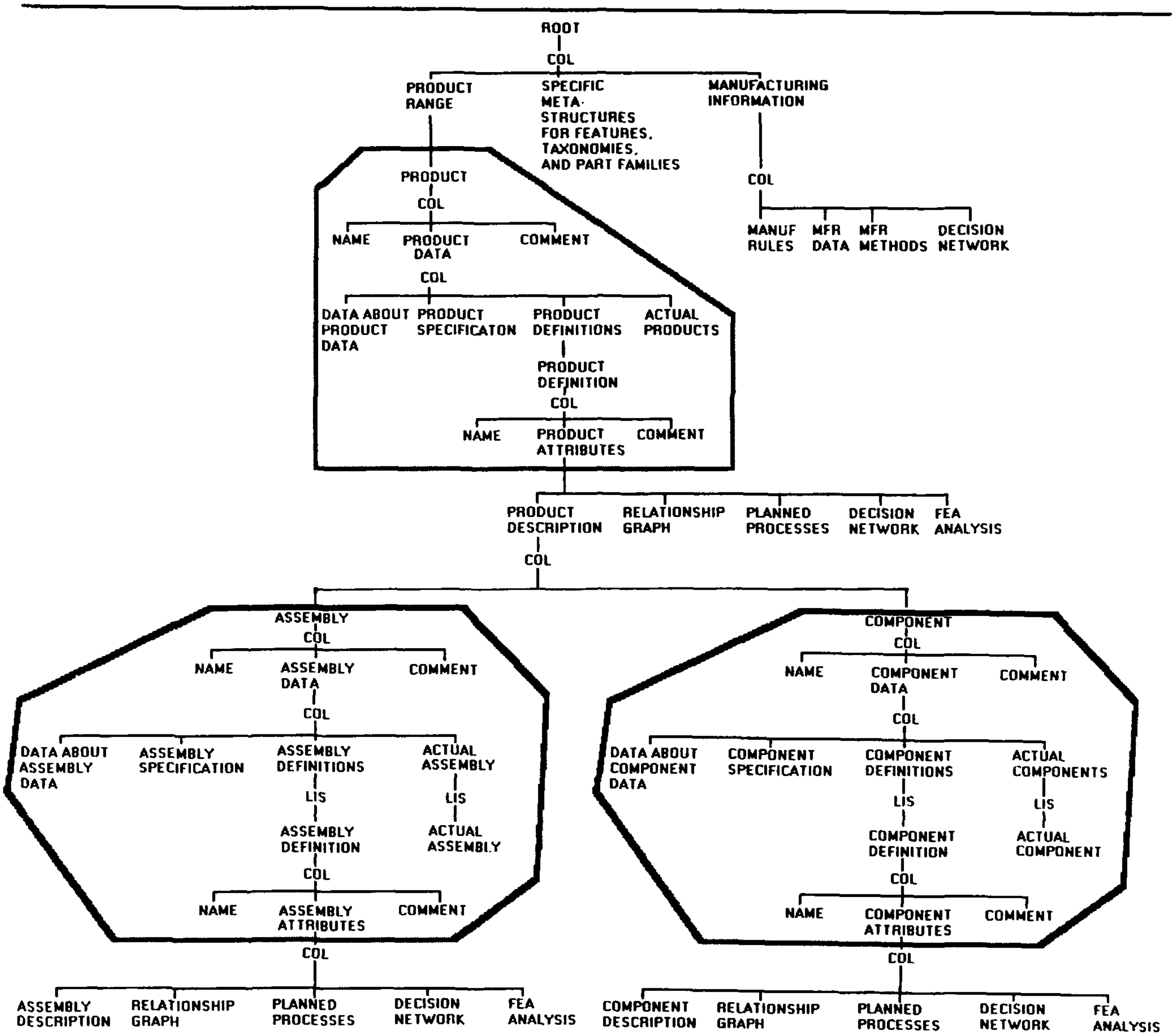

Fig. 3 — Fragment of hierarchical product data model

the previous data models I have seen in industry are, in some sense, mimics of a product design/development process. Hence they contain essential elements of time and logical precedence, indicating data that are needed first, then second, and so on, plus the data flows as inputs and outputs.

The Leeds structures are not typical time-based models of design processes like PERT/CPM diagrams (and of course they need not be). Instead, they are something else, but it is not clear what. They are not just descriptions of the product because they have references to engineering analyses high in the structure. These references correspond to a time relationship in the design process: when an assembly model is available, do an FEA on it. Why are these FEA references there? How did someone decide that they belonged there? What is the relationship, in other words, between this structure and its designer's image of the time-based design process?

This discussion also points out, again, the fact that one can include data in a "product" data model that actually support or even describe the design process rather than the product itself. This is an important and perhaps paradoxical point. It may be an admission that there is no such thing as pure product data. A similar point is made by Prof. Herb Voelcker[13] of Cornell: 50 years ago designers

annotated drawings with notes like "drill and ream." That is, the designer put process planning instructions on the drawing. In more recent times, the ideal has been to separate design from process. The designer says what tolerances are needed but a process planner decides whether or not reaming is needed to achieve the tolerances. The choice may hinge on what machines are available or how many of the part are needed. This is a nice ideal, but it plays a big part in separating *design* from *design for manufacture*. The disadvantages of this separation are now clear, but there is still no agreement on whether designers should resume saying "drill and ream." Similarly, product data designers are investigating whether, when, or on what part sets FEA should be done.

Many people familiar with electronic product design and manufacture (VLSI for example) point out that one of the main reasons why VLSI has advanced so rapidly is that designers need not concern themselves with process issues. The process limitations are represented by design rules that can be expressed purely in geometric terms (minimum radii, minimum line width and separation, etc.). These rules can easily be checked and enforced by the computer. Furthermore, most elementary functions in VLSI are represented by standard cells of basic devices and interconnects that the designer can lift from a library. This leaves the designer free to think almost completely in terms of functions.

If the Leeds work is a harbinger, then it adds evidence that mechanical product design will never be accomplished as pure data manipulation at the function level the way VLSI design is.

A final point: this research clearly shows the influence of sophisticated computer science, provided not only by collaborators Prof. Peter Dew and David Holdsworth from the Computer Science (CS) department but also by staff members Susan Bloor and Alison McKay who combine engineering and CS backgrounds. Dew spent several years working on VLSI data architectures and automated design methods. None of the German CAD research observed on this tour of Europe contains anything like this level of CS participation or sophistication.

Ecole Nationale Superieure des Arts et Metiers (ENSAM)

The ENSAM Laboratory for New Product Concepts in Paris is an interesting mix of research, teaching, continuing education, and industrial consulting. Without the aid of fancy computer tools, this group has carefully and pragmatically elaborated a product development strategy that is considerably richer than typical concurrent engineering methods. Products are described at three levels, and roles for each of the actors in a CE process are spelled out for each level. This is considerably more sophisticated than just forming teams and letting them figure out what to do.

The procedures they have so far constitute a manual methodology rather than computer tools. The main steps in the process that they describe are the familiar ones of identifying the need, converting need statements into function statements, searching for possible implementations, choosing one, testing and prototyping, and so on. In this regard their work sounds like that of Prof. Beitz and others.

However, most laboratories take a heavily engineering-oriented approach whereas the ENSAM people work at a more conceptual level and are not as technically focused. Interesting aspects of their methods include making a semantic characteristics list to describe a product, making diagrams that show how each part or assembly satisfies each requirement, and looking at a product at different levels called "minimal parts," "architecture," and "individual parts."

The Ph.D. work of M. Le Coq attempts to tie all of this together by laying out the elements of a systematic product design method. Every product development project has four components:

1. The *product concept itself* is a clear statement of the first idea of how the needs might be met, stated in such a way that all the people who must participate in the design process can understand it.

2. The *procedure* is a statement of the actions that the design team must carry out in order to design the product.

3. The *structure* tells the designers how they must interact with each other in carrying out the procedure. Two different types of structure are identified: the multidisciplinary team method and the series of experts method.

4. The *tools* comprise engineering, computers, and so on, plus their software and methods.

The procedure operates at three conceptual levels: the minimal set of parts or elements that can satisfy the requirements, an architecture (spatial arrangement and physical connections) that links those parts, and all the individual parts in a complete design. These are pursued in that order. The main job of the designer is to think up architectures and their minimal parts; the engineer must determine the flows of energy, fluids, heat, stress and so on between these minimal parts. In the best of situations, the work is carried out by a designer-engineer who can work at all levels. This procedure is similar in most respects to typical product development methods.

The interesting part of this is a chart (Table 4) that shows how each of the players in a multidisciplinary design team might see the minimal parts, the architecture, and the individual parts.[14] For example, the assembly person would look at the minimal parts from the point of view of trying to standardize them and their required assembly processes. He would look at the architecture from the point of view of assembly sequences and process optimization. Finally, he would look at individual parts to see how to speed up their assembly and lower the cost of doing so on an individual part basis. At present there are no firm plans to computerize this procedure. Instead, ENSAM teaches it, mostly to small firms.

Ecole Polytechnique Federale de Lausanne (EPFL) Institute de Microtechnique

The laboratory of Prof. Jean Figour is devoted to design of automatic assembly systems. These typically consist of transfer systems and a series of fixed stations or stations containing limited-motion, fully programmable robots. Equipment and system design methods capable of handling different versions of a product to another are a central feature of the research. It covers all the interrelated aspects of system design:

- assembly sequence analysis of products
- design for assembly
- assembly machine elements
- assembly system controllers and languages for driving them
- discrete event simulation languages and software
- continuous event simulation languages and software.

The simulation software is similar in many respects to others of its kind, but it is well-presented on Silicon Graphics displays. The discrete event version uses Petri Nets to model the system. It can simulate not only the physical activities of the machinery but also the operational aspects of receiving an order and processing it. Simulation of delivery of multiversion products from semiflexible systems is a key aspect of its capabilities.

The continuous event version combines animation of workstation and human activities with statistical performance displays on the screen. Behind this software is the capability to design the system from a library of actuators and machines whose cycle times are known or calculable. Thus it will be of interest to companies that build such systems. Some of the above research will apparently play a part in the SCOPES project.

More interesting from the research point of view is recent unpublished work on assembly sequence derivation. It is based on the disassembly method, as is most recent work on this topic. Parts are analyzed via CAD models to see if they can be removed in one of the cardinal directions *X*, *Y*, or *Z*. A node-node incidence matrix is used to record the blockages found. (A 1 in the *X*: A-C entry means that part C blocks the exit of part A in the *X* direction.)

An interesting feature of this work is the use of powers of node-node incidence matrices that model the interconnection diagram of the parts in an assembly. An entry of "1" indicates that a part is directly connected to another. The square of the matrix contains "1" to indicate that two parts are separated by one part; that is, there is a path of

Table 4—Three Levels of Product Specification and the Roles of Team Design Process Participants at Each Level

	Minimal/indispensable parts	Architecture	Parts
Marketing, Sales	Image, impact of technology, sale price	Market niche or level, diversity, differentiation, cost	Finish, cost, market niche or level
Design, Styling	Concept choice, technology	Market niche, image, uses	Appearance, shape, visual and tactile aspects
Ergonomics	Scenarios for use	Scenarios for use, macro actions	Micro actions, visual and tactile aspects
Design Office	Technology, choice and realization of actions and flows of energy and information	Respect for constraints on the flows based on the concept requirements	Optimization of flows, shapes, fastenings, and connections
Fabrication	Technology and standardization of processes	Process choice, complexity of parts	Process optimization
Assembly	Technology and standardization of processes	Choice and optimization of processes, trajectories, sequences, tools...	Optimization and realizability of cycle times, automation
Testing	Technology and standardization of tests	Testing scenarios and strategies, creation of functional subassemblies	Interfaces, system connections, repairs
Maintenance	Strategy, cost and exchange of parts, warranties	Accessibility for diagnosis and repair, changes to the system	Ease of removal and placement, special tools
Purchasing	Policy, constraints on suppliers, make-buy decisions		
Recycling	Standards and constraints (toxicity...)	Homogeneity of materials, access to dangerous elements	Material choice, removability, disposability

length 2 between them in the interconnection diagram. Successive powers of this matrix are able to elucidate longer paths.

This property is used to find how many parts intervene between one part and another that block its removal in a given direction. Another matrix is constructed showing if parts are fastened to each other, by screws for example. If this matrix is combined by inclusive OR to powers of the interconnection matrix, groups of parts that are fastened together can be deduced, thus leading to the ability to identify one type of subassembly. Stability of subassemblies can be checked in a similar way.

This work is still in a preliminary stage, and no large-scale tests of the algorithms have been made. A definitive explanation of the method awaits a formal publication.

Summary

The research laboratories visited are carrying out a wide variety of activities. These can be grouped roughly as

- concept design methodologies and aids; and
- detail design improvements, including some engineering aids in the form of AI systems.

Approaches to concept design usually take the form of "inspired sketch pads" that permit a designer to call forth library functions like "motor" or "bearing" and hook them together into systems. These systems can be simulated or analyzed in other ways; they can then be converted, element by element, into specific geometry. Analyses are supported by various knowledge and rulebases. At least, that is the goal. Most of the difficult conversions are done by the designer, not the computer.

Research into detail design comprises various efforts in feature-based design, generalized sculptured surfaces, and geometric realizations of specific engineering systems, such as machine tool spindles. Some laboratories support the designer with rule and knowledge bases while others are trying to create connections to engineering analyses like vibrations or finite elements. Efforts also exist in linking mathematical and geometric constraints to geometric modeling and feature-based design.

The researchers do not seem to be aware of the forces and events driving the companies. They see design the same way they have for years: as an individual activity that needs to be supported by computers—to design a single product, a single person must reduce a set of requirements to a geometric description, observing the needs of manufacturing and revising the design as necessary to achieve those goals. Companies see this aspect of design but also see something most researchers do not: a complex multiperson activity that must be managed, dominated by huge masses of data and sharp conflicts between the needs of various constituencies.

Both researchers and companies agree that design is a progressive process, but researchers see it as an orderly quest. By contrast, companies live with wild gyrations in risk, strong differences in approach by different design team members, and problems too big for one or even a few people to comprehend and manage. These differences are not just a matter of style but represent real gaps that strongly affect what both researchers and industry think computers should be able to contribute as well as how those contributions should be described and achieved.

The experience of actually designing a complex item appears indispensable if one is to comprehend the process and aim research at its most difficult points. Too few design researchers have such background. The exceptions are immediately obvious. In FRG, for example, most professors are former industry designers or engineers, and bring a very technical attitude to their research, with interesting results. But many of these people got their industrial experience before major advances in computer science occurred, and they do not integrate such knowledge with their research. This gap is apparent in most other countries as well. Thus actual design experience is necessary but not sufficient. New collaborations are needed, not only between researchers and companies, but between engineering and computer-oriented researchers.

Furthermore, the trend to adopt AI methods and neural nets may be suffering from lack of basic engineering knowledge or absence of sufficient analytical foundation. Expert systems have not delivered on the most optimistic hopes and have

instead found a place as training aids and ways of accessing standard information of various kinds. This is a useful result but not one on which long-term improvements in design methodology are likely to rest. Opportunities to link AI methods with more analytical and fundamental expressions of engineering are needed.

In the face of these gaps, more than one person in industry questioned whether universities really can do research in design and manufacturing. An alternative offered was to let industry set the agenda since it has direct contact with the problem, while universities should be "centers of excellence" in specific areas. Many companies now follow this formula. The trouble with it is that industry too often sees limited horizons or the problems of its operating environment alone. The ability of researchers to find generalities and underlying principles should be valuable in forming the research agenda and finding broadly useful solutions. For this reason alone, universities should not be relegated to centers of excellence, which in reality would amount to consulting practices.

TRENDS IN GOVERNMENT FUNDING OF RESEARCH

Government funding for research in Europe comes from two different sources, each nation's own research ministries plus the European Community (EC) programs. EC programs include the European Strategic Programme of Research and Development in Information Technology (ESPRIT), Basic Research in Industrial Technologies (BRITE), European Research in Advanced Materials (EURAM), and Research and Development in Advanced Communication Technologies for Europe (RACE). These programs operate under rules that require partners from at least two member states. Projects usually contain both companies and universities and are initiated by companies in response to calls for proposals. Unlike design and manufacturing research in the U.S., European and EC research in these areas has a permanent and deep applied component. This component is enforced by the required industrial participation as well as requirements, especially strong in the U.K., for a defined technology transfer plan in most projects.

ESPRIT and BRITE-EURAM are major components of the EC Framework program for R&D. For the time period 1991-94, the total Framework funding is 5.7 billion ECU. Of this, ESPRIT has about 2.2 billion and BRITE-EURAM has 748 million (one ECU = $1.30, approximately, as of Sept. 21, 1992). Table 5 provides a breakdown of funding by topic area. ESPRIT and BRITE/EURAM programs have been combined in this table.

Major changes, reassessments, and new programs are emerging within the EC's research programs. Two research Directorates (Computer Integrated Manufacturing and Engineering (CIME) in ESPRIT and portions of BRITE) have recently been merged to eliminate overlaps in objectives and projects. In addition, the Intelligent Manufacturing Systems (IMS) program proposed by the Japanese is causing important international connections to be established and new methods of cooperating to be developed. Underlying the policy issues are basic research questions such as whether manufacturing research is important enough to be funded separately, and whether a top-down application of information technology R&D alone can solve problems in design and manufacturing.

BRITE/EURAM Program

This program sponsors research into materials, manufacturing processes and design, and computerized methods of operating complex factories. The budget for 1991-1994 is ECU 748 million, allocated as follows:

raw materials and recycling	12%
materials in general	35%
design and manufacturing	45%
aeronautics	8%

The latest round of funding drew proposals in April 1992 and another round ends in February 1993.

The program's former director, David Miles, noted that BRITE was designed to be a bottom-up program driven by the needs of users, that is, manufacturing companies. However, these needs are not well understood by researchers, indeed not well understood by most companies. The main reason appears to be lack of awareness of system

Table 5—1990-1994 EC Framework Budget

Program Element	1990-1994 Budget (Millions of ECU)	Program Total
I. ENABLING TECHNOLOGIES		
1. Information and Communications Technologies		2,221
Information Technologies	1352	
Communication Technologies	489	
Telematic Systems	380	
2. Industrial and Materials Technologies		888
Industrial and Materials Technologies	748	
Measurement and Testing	140	
II. MANAGEMENT OF NATURAL RESOURSES		
3. Environment		518
Environment	414	
Marine Science and Technology	104	
4. Life Sciences and Technology		741
Biotechnology	164	
Agricultural and Agro-Industrial Research	333	
Biomedical and Health Research	133	
Life Sciences and Technologies for Developing Countries		
5. Energy		814
Non-Nuclear Energy	157	
Nuclear Fission Energy	199	
Controlled Nuclear Fusion	458	
III. MANAGEMENT OF INTELLECTUAL RESOURCES		
6. Human Capital and Mobility		518
	TOTAL	5,700

issues, such as inability to write a proper specification for a flexible manufacturing system or determine the reasons why it is not operating properly.

To bring more structure to his research program, Miles has been looking at the whole supplier chain to identify the necessary steps in producing products, find the technology gaps, and focus research on them. He notes that this approach has a shortcoming with regard to design, whose necessary elements and procedures are not well understood. In particular, the constraints on products are changing rapidly, with recycling and environmental effects increasing in importance. No one knows how to systematically take these into account during design, which is the only place such accounting can occur. On this point he cautions that too much responsibility can be placed on design. This will over-burden it—making it so complex that no one can accomplish it, especially small businesses.

ESPRIT's CIME and IMS Programs

(CIME - Computer Integrated Manufacturing and Engineering; IMS - Intelligent Manufacturing Systems, which are discussed later in this section.)

The ESPRIT program has had two Phases; it is now in Phase III. The funding history is:

- Phase I (1984-88): ECU 1.5 billion (12% was for CIM)
- Phase II (1988- 92): ECU 3.2 billion (16.5% for CIM)
- Phase III (1991-94, deliberately overlapped): ECU 2.7 billion (20% targeted for CIME)

The "E" in CIME is new with the start of ESPRIT Phase III in 1991 and reflects a strategic decision to apply CIM methods and technologies in areas outside of traditional manufacturing, such as agriculture and construction. This decision appears to include extending the CIM idea beyond data exchange, networks, and traditional metal cutting to include the whole product life cycle. These new areas are the source of more proposals than the EC expected, so budgets in the traditional areas are being squeezed. It is my impression that Mrs. Patricia Mac Conaill, the Head of Division responsible for these programs, has had to fight very hard to keep funding active for CIM. Perhaps this is due in part because manufacturing research is not viewed in the same light as more traditional discipline-oriented areas.

A major role for her has been to foster and develop a community of researchers and government officials in the member states who agree on a broad research agenda. The differences in culture and style between the member states of the EC must always be kept in mind. For these reasons, she is particularly pleased with progress in data exchange standards and a technology diffusion program called CIMEUROPE. The latter helps small and medium size enterprises (SMEs) find partners for technology transfer, consulting, business contacts, and EC research program participation.

Another impression gained from talking to her as well as to others is that the EC programs, regardless of degree of technical success, have over many years achieved something Europe has never had before, namely, this community of people in industry, universities, and government who understand some of the technical challenges and now know each other as well. Mrs. Mac Conaill is one of the builders of this community. She has also kept up informal collaborations in the U.S. with the National Science Foundation, the National Institute of Standards and Technology, and until recently, CALS.

CIME Program

In the CIME program, funding averages ECU 130 million per year; it covers 60 projects now with 60 more coming on stream next year. The average is thus a bit over one million ECUs per project, each lasting several years.

The overall goals of CIME are to improve European industry's competitive position by:

- applying IT solutions in processes and products, with emphasis on applying;
- seizing new markets; and
- producing cleaner industrial processes.

The application areas are discrete parts manufacturing and its associated processes; engineering, mining and extracting of materials; construction; and agriculture. The "tools" for this push are IT architecture and infrastructure; management and design of enterprises (all the necessary software for CIME); and mechatronics, robotics, and sensors (all the hardware necessary for CIME).

The architecture issues to be dealt with include open architectures and neutral data, "information engineering and management," how to migrate to an open environment, and how to achieve cost-effective integration of software tools. These are user-driven concerns and are similar to priorities of many U.S. software researchers. The emphasis on user-driven is a new one in ESPRIT, however.

Design and management of enterprises includes

- integration of software tools into systems
- how to implement software changes, i.e., the human and organizational issues
- concurrent engineering (which here means many designers working on the same design at the same time)

- manufacturing and the environment
- consideration of the entire logistical chain from raw material to end user
- economics and performance monitoring of CIME
- quality management.

Mechatronics includes

- design and modeling of multidisciplinary items
- coherent database and interface specifications for multitechnology activities
- micromachines.

These are very extensive lists and appear to reflect some of the cumulative effect of long-term community discussions mentioned by Mr. Miles, as well as some obvious overlaps with BRITE.

Accomplishments cited include the program's influence on standards, especially the STEP process; some neutral data definitions; new products such as open architectures, interface boards, CAD tools; several actual CIM implementations; and enhanced education and training programs.

Intelligent Manufacturing System (IMS)

The IMS was presented to ESPRIT by the Japanese in November 1989. After the original Japanese call for proposals, the U.S. Department of Commerce requested that the contacts be handled under the provisions of existing U.S.-Japan agreements. A long series of informal trilateral discussions has taken place seeking to determine methods of funding, clarify ownership of intellectual property rights (IPR), and reduce the academic character in favor of one more oriented to industry.

Current status (summer 1992) of these negotiations is as follows:

- Instead of launching the IMS directly, there will be a feasibility study lasting about two years, during which the "modalities" (ways of working together), IPR, funding mechanisms, and overall viability of the IMS will be assessed.

- A complex committee structure has emerged, giving rise to some concern that bureaucracy will dominate the program. This structure consists of a Steering Committee, a Technical Committee, and an IPR Committee.

- The Technical Committee has recently agreed on six research themes for the feasibility study period:

1. enterprise integration
2. global manufacturing
3. system component technologies
4. clean manufacturing (environmental concerns)
5. human and organizational aspects
6. advanced materials processing.

United Kingdom Funding Trends and Strategies

Until five years ago, English universities had line-item budgets from the government that were based on "planned" enrollments. If enrollments fell short of the plan, the universities kept the extra money. This has been changed so that funds are now based on actual enrollments. The government also gives funds that match industry contributions and contracts. This trend has forced research into a more applied mode in order to capture industry support. It also has tended to tilt the research more toward bottom-up in the sense that particular processes or design steps must be emphasized, even if there is a generic goal in the minds of the researchers.

Another change that is affecting universities is a triage by the government. The result of the triage will be three classes of universities: those that have broad curricula and unrestricted research opportunities, those that will revert to teaching only, and a group in the middle with teaching and limited research topics. The same triage is happening in the FRG.

The nature of government funding for design and manufacturing is also changing. The two sources, SERC (Science and Engineering Research Council, like our NSF) and DTI (Department of

Trade and Industry, like our Department of Commerce) have different goals, funding sources, and management techniques. SERC's design research is currently a single program, not an ongoing process with a recurring budgetary line item.[15] DTI, on the other hand, funds more broadly defined manufacturing research through its line item for the ACME (Application of Computers to Manufacturing Engineering) directorate within SERC. A joint DTI-SERC steering committee called the Advanced Manufacturing Technology Committee (AMTC) oversees the ACME program. AMTC operates in a sort of contract mode rather than a grant mode. It establishes milestones and frequent reviews. It can stop a project if it is not making progress, and it often does so. Since its founding in 1984 ACME has spent £40 million.

The November 1991 edition of the ACME Strategy booklet defines what looks like an "industrial policy" and appears to me to be

- declaration of a mission to use research funds to help British manufacturing;
- recognition that something beyond "basic" research is needed to help manufacturing;
- identification of classes of research and industries;
- conscious allocation of projects and resources to some of these classes;
- recognition that manufacturing spans technical, social, and financial domains, and that spanning research is needed;
- *time-line* structuring of each project from idea to "product" so that suppliers and users of potential results are part of the project from its initial planning stage until its conclusion (the concurrent engineering of research projects?)
- *cross-disciplinary* structuring of the projects requiring collaborators from different backgrounds, companies, and universities; and
- rejection of collaboration or diversity for its own sake.

Close reading of the strategy book indicates that:

- overall, research funds in manufacturing will shrink over the next three years;
- since several university centers of excellence have emerged over the last few years, it is they that will get the bulk of the remaining funds, while others will be squeezed out;
- funding for robotics and textile manufacturing will be reduced while funds for management and planning research and for manufacturing processes will rise; funds for CAE, integration methodologies, and advanced production machines will remain the same (integration was boosted significantly last year);
- compensation for the funding falloff will be sought from industry;
- projects will be actively monitored; and
- the entire portfolio of projects and research topics will be reviewed in two years.

Funding Trends in Europe

Along with many other things, the structure and funding of the EC research programs attracts comment and internal reviews. As noted above, several obvious overlaps between BRITE/EURAM and ESPRIT have recently been removed. Other changes may occur as the EC attempts to improve the technology transfer from its projects.

National research funds in several countries are on the downturn. This is especially evident in the Federal Republic of Germany, where a general contraction due in part to financing unification has hit both research and education. Grant funds are becoming hard to get, even for famous research institutes. Universities are being forced to reduce the number of faculties (roughly equivalent to departments). In several countries (U.K., FRG, France) increased attention is being focused on Polytechnics (Fachhochschules, Ecole Polytechniques, respectively) in an attempt to increase the number of trained engineers and technicians, possibly at the expense of Ph.D.s.

The downturn in national research funds has forced more and more universities and companies to turn to ESPRIT. The result is more projects with numerous partners, with all their advantages and disadvantages, plus a lower likelihood of obtaining funds. Several researchers are frustrated and have seen major projects stop for lack of renewal money.

Comments

It is not clear that multipartner projects are a good idea. From the point of view of research output, they are hindered by problems of coordination as well as communication. Typically projects have 5 or 6 participants, but some have 20. From the point of view of fostering European unity and mutual understanding among EC member states, as well as between companies and universities, the projects probably are beneficial in the long run. The researchers themselves, both in industry and universities, often remark on the disadvantages while the EC program administrators often point out the advantages.

It takes a lot of discussion to bring about big international projects; both Japan and the EC have benefited from existing (inter-) national infrastructures for doing these negotiations. The U.S. has much less experience in this area and needs to get more soon.

A French research manager said that ESPRIT projects last three years, of which the first 1.5 are used to establish a common technical vocabulary and understanding of the partners' goals and methods. An American Professor of Management at Cranfield whom I met on a bus said, "We all speak English and look alike so we assume that our cultures are the same. This mistake takes a long time to discover and correct."

A good deal of underlying mistrust must also be overcome. Several Europeans told me that they do not like the IMS because it is too likely to result in one-way technology transfer to Japan. A major goal of the feasibility phase should be to establish two-way transfer and show how it can be made a permanent part of the program.

Finally, the structure of EC and U.K. programs has both benefits and drawbacks that need to be considered. It is useful to have industrial participation in research projects, as well as to enforce a degree of technology transfer. Direct contact with industry's problems is usually revealing to researchers, who find the complexity of real problems challenging. On the other hand, longer term research may fail to obtain funding, either because companies do not see where it will lead or because universities deliberately restate the objectives in order to appeal to industry, on whose funds they increasingly depend.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

I have drawn several conclusions from this survey:

1. Design research is extremely diverse. Everyone says "design" and means something different.

2. Most design research focuses on the technical activities of an individual designer, attempting to increase the quality of his/her output.

3. Companies do not see much in ongoing design research that appears useful to them. The main reasons are that some research is quite far ahead of industry's self-perceived needs, that industry is not skilled at recognizing potentially useful research, and that researchers' view of design is too different from industry's view.

4. When asked to identify their problems, industry people focus on organization and management of the design process, finding out its true structure, requirements, and information content; they do not cite problems with the quality of individual engineers' work. This priority, in advanced companies, dates back as much as 15 years, while in lagging companies it is as recent as 2 years. (Companies *do* care about the quality of individual designers even if they do not talk about it. But they deal with that issue differently, usually with in-house training. In the U.S. one often hears complaints that university graduates are not well-prepared.)

5. The most advanced companies (in Europe and Japan) view computers primarily as an aid to this information management problem and only secondarily as devices for doing calculations or defining geometry. (From Nissan: "We are presently defining our next-generation working style

and will write or buy software to suit." From Aerospatiale: "We introduced design-build teams in 1975 and CAD in 1977. Computers, from the outset, were used to support this new way of working. Our database is the most important element.")

6. Companies are evolving increasingly sophisticated approaches to product design and need new tools to support these approaches: design of product families, of products that will evolve into different models, that must be made in a JIT environment and sold into complex and shifting markets, or that will be made in different countries using different mixes of people and machines. These are all "integration-rich" areas that pose quite different challenges from those recognized and supported by computer tools in the past.

7. The CAD vendors have followed rather than led this process. Their emphasis used to be on accurate geometry, which is important but not an end in itself. More recently the emphasis has shifted to data management, engineering knowledge, and "integration-rich" processes like assembly.

8. Industry's experience with Concurrent Engineering has revealed many of these new requirements as well as the need to better meet customers' needs, exchange information in new patterns and sequences, take account of assembly, predict costs, improve reliability, account for recycling regulations, and so on. More data, diverse and conflicting, must be found and combined, in order to respond. New algorithms are needed to sift and combine data, resolve the inevitable conflicts, and reach good design decisions.

9. Unless they commit to defining the requirements and writing the necessary software themselves, the companies face a difficult task explaining the requirements to the vendors. However, the skill to write this software and the commitment to maintain it do not exist at very many companies.

10. The knowledge needed to respond to these challenges generally does not exist inside the CAD vendors. Typically they offer a new product or capability and, if "successful," they are inundated with demands to change it to do what is *really* needed. This "generate and test" approach is not very efficient. Since the vendors are small, they often must choose which customer to respond to and hope that the others will like the result. But sophisticated design methodologies are increasingly industry-, product-, or company-specific.

11. Rarely do companies try to explain these new requirements to design researchers, whose research does not reflect much awareness of them. Much of the U.S. research on Concurrent Engineering, for example, reflects awareness of the need for electronic communication, again necessary but far from sufficient.

12. Thus the companies must supply the majority of the knowledge and experience required to define new design paradigms and software requirements. The "right" strategy of combining the skills and knowledge of users, vendors, and researchers has not emerged and remains a major barrier to improved design methods.

13. Only the largest companies have the resources to take on this task themselves. Medium and small size companies are left to buy what the CAD vendors offer, compatible with lower cost computers. Only in Japan is there an approach to this problem: the multi-tiered supplier system in which higher level companies teach new methods and, recently, provide software to their next-lower tier suppliers.

I am convinced that design researchers can play an effective role as design goes through a

revolutionary and exciting phase. To make this role possible requires establishment of new technology transfer mechanisms and changes to the research agenda.

The gist of the recommendations that follow is that the design process needs additional and broader attention by researchers, working together with end users and CAD software suppliers. The collaboration must be structured this way because the design process and the computer tools are so intimately linked. The users have the clearest view of design, while the suppliers have the best chance of delivering well-designed tools; the researchers have the longest view, a (possibly) better view of allied knowledge that could be brought to bear, plus the drive to generalize and find scientifically based solutions.

Recommendations

Define a focal issue for design research: to determine the required content of a product data model.

The design research community needs a large focal issue to work on together. Design research is at present too fragmented; a critical mass has not formed behind any particular topic. This is understandable, given the complexity of design and its relative immaturity as an intellectual field. Too many different things are called "design" and not enough differentiation and prioritization have emerged. The physicists are all looking for the top quark. The atmospheric scientists are all trying to find out where the CO_2 is stored. The molecular biologists are mapping the human genome. The latter two activities are especially application-driven in the long term, even if the immediate results must be fundamental advances in knowledge.

In addition, many of the ongoing research activities face uncertain futures because the path to application is blocked by some basic knowledge gaps. The major gap is the lack of a clear concept of a product data model. Ongoing efforts in tolerance representation, feature-based design, assembly planning, and design critiques, to name only a few, will have nowhere to go if there is not an agreed-upon data representation that has a place for them. Their internal data structures are presently developing independently, and there is the threat that long-term results will be mechanically and (worse) conceptually incompatible.

Not only is a "place" needed, but each of these areas, and others, strongly interact with each other during any challenging design. Thus the research results cannot stand alone in the data model but must be interconnected. An understanding of how they interconnect is presently lacking, another serious barrier.

In recommending a long-term effort at developing a product data model (see below where this is spelled out in detail), I am taking the approach I observed in Japan, namely that efforts at integration need to begin *before* the separate islands are completely understood. Integration brings a totally different learning experience, uncovering sometimes fatal incompatibilities in basic assumptions, methods, and data representations among the previously developed islands of (design) automation.

Shift research emphasis away from expert systems and toward fundamental engineering models of phenomena and activities that are presently approached through expert systems.

The present trend to apply expert systems and neural nets to design needs to be regarded as a clue that basic engineering models are lacking in many areas of design. This "lack" may mean that the knowledge is genuinely non-existent or that it exists but has not been systematized and applied in design methodologies. We need to identify classes of design problems where engineering knowledge could feasibly be improved, and then mount research efforts to make those improvements.

Broaden the scope of design research to encompass the industrial contexts.

The design process needs to be looked at by researchers in a new way. *A product design is a business concept that contains many engineering problems; it is not a set of engineering problems in a business context.* The current research view of design as a purely engineering issue needs to be broadened. The problems of business strategy, data management, conflict identification, and process improvement all need attention. New models of design processes are needed, models that explicitly represent iteration, conflict, constraint

propagation, negotiation, and tradeoffs. These issues are bound to be very broad and incommensurate, and people are likely to be left to make the final decisions. That is, an algorithm for resolving basic design conflicts should not be sought as a top research priority. Instead, novel data access, assimilation, and presentation methods may be preferable. Naturally, solutions to these challenges will have to be tied closely to emerging models of product data, inasmuch as the design process appears to be the reason why much of the data are needed.

Broaden the engineering scope of design research.

New kinds of design challenges need to be recognized and made the subject of research. These include design of product families, design of products that will be made under specific production constraints (very low volume, Just-In-Time, recyclability, multinational production, for example), and design/production by multiple firms. In the past, a lot of attention has been devoted to *new manufacturing processes* to meet such challenges, such as intelligent robots for low volume and model mix production. I am here suggesting that *product design* be regarded as the weapon of choice for attacking these problems. There is plenty of precedent for this strategy in industry, and it has generally been quite successful.

Define new kinds of intermediate or partial designs to help resolve problems during concept design.

The basic challenge of predicting future manufacturing and cost problems during concept design is repeatedly asserted by companies. This problem contains an inherent paradox, namely, that future detailed information may completely upset decisions made when only rough information was available. The kinds of information wanted at each stage of the PDP must be pruned to what is most useful and reasonably possible to provide. New forms of intermediate data are needed. For example, to support assembly planning, one needs part "designs" whose shape consists of rough "keepout zones" while only their interfaces to other parts are modeled accurately. By using such data, designers could answer many of the main product architecture questions but would have to accept the possibility that some decisions would be upset later. This compromise is not only necessary but probably worth making in exchange for the benefit. Such data would later be overwritten by the final design, but would nevertheless have served their purpose in supporting the design process.

Study and improve the design technology transfer mechanism.

Better technology transfer paths need to be developed so that design research results have a better chance of being used. This topic is separate from the need to provide a common data representation. The issues here involve relationships between companies and industries. The basic structures of the industries (where new ideas come from, how information is passed around, how development is paid for, etc.) need to be better understood so that the blockages can be removed. Examples of successes and failures need to be developed in detail so that lessons can be learned.

Main Recommendation

Design research would benefit from having a common focal issue, assuming that issue were chosen carefully. The characteristics of a well-chosen focus might be that:

- it can be crisply defined and made specific (not: "better design," "a science base," "more process knowledge");
- researchers, users, and CAD vendors agree that the result will be widely useful or adaptable, perhaps even generic (i.e., it is ultimately application-driven and derives its content from a vision of how it will be used);
- it is obvious that increases in basic knowledge will be needed to achieve it (i.e., it has genuine intellectual content and cannot be achieved with today's knowledge);
- as it evolves it provides the basis for other research issues to be attacked, reflecting a prioritization and sequencing of the knowledge development process in design;

- it provides meaningful roles for researchers, users, and CAD vendors to play in its evolution;
- it does not require detailed or specific knowledge that only a single company would have or that describes a single process.

As a candidate focus issue I would like to offer the Product Data Model (PDM). The issue can be stated briefly, although the "answer" will take time and effort to produce and will continue to evolve: **"What information belongs in a product data model?"** Given the diversity of the community and the intellectual difficulty of design, I would judge this candidate a success if even 30 percent of those asked agreed with its choice.

I will not dwell on other issues that might have been offered. I lack the time and wit. However, I can justify the central place occupied by this issue by giving my reasoning, indicating that it lies at the end of a logical chain that can be converted into a research plan. This chain passes through other candidate issues on the way to the PDM.

The chain begins with the observation that companies that know a well-thought-out product development process (PDP) is crucial to their success. An emerging model of the PDP is that of gathering, manipulating, transforming, and transmitting information. A useful analogy has been made between design as a process that transforms information and manufacturing as a process that transforms material: While manufacturing consists of a series of operations performed on material, design consists of a series of questions asked of an information base, a plan for when to ask each question, sources of data to support answering, and a destination or destinations for the answers, which are used to help answer later questions.

The answers come from two types of sources, namely other databases (including people's experience) and algorithms. These algorithms can be as simple as "Call Joe" or as complex as optimizations, crash simulations, or other advanced methods. But any algorithm, however simple, will not function if the needed data are not available, and will not function efficiently if the data are not arranged congenially. Given the scale of advanced design problems (hundreds of parts, thousands of finite-element cells, tens of thousands of assembly sequences), inefficiency can be equivalent to nonfunctionality.

[A generic issue in database design involves what data should be explicitly represented and what should merely derivable from explicit data. This issue is finessed here, on the assumption that even derived data are available in some sense. It is not a trivial issue but neither is it one whose resolution stands in the way to first order. We should first decide *what data* must be available somewhere and then decide, based on efficiency, where/how it should be stored.]

Thus the content and structure of design databases are driven by the needs of the algorithms that will use them. In turn, the algorithms, their inputs and outputs, are then driven by the structure of the PDP. So the PDM is at the end of this logical chain—the child of the main deliberations concerning how PDPs should be structured and how their inherent questions are to be answered.

One might conclude at this point that the PDM cannot be specified generically because each company or product will require a different PDP, giving rise to a different PDM. In any specific case this is likely to be true. But one can also argue that any particular PDM will have elements that can be seen in a more generic data model. There may be intellectual and practical advantages to seeking a broad model from which to select elements for specific applications rather than to continue to discover new data that should have been present in the first place. Faith in the usefulness of a generic solution surely underlies the ongoing PDES/STEP activity.

I take the generic PDM view because I have been repeatedly surprised during this study by the wide range of kinds of data that people have already identified as being essential to product design, data which are (a) not presently available except perhaps in people's heads; (b) not supported by existing or foreseeable "CAD" products; and (c) not being given high priority by the design research community. Furthermore, I get the impression that designers themselves are surprised by what data they have discovered are necessary, and that they are prepared to be surprised in the future. The main surprises will come from the need for data that are about the design process. Table 6 contains an example if this kind of data.

Table 5. Discovering New PDM Requirements

1. Assembly is receiving increasing attention and is playing a role in early phases of product design that it never played before. Past concepts of product data have focused on representing individual parts because, based on perceived cost, fabrication is the most costly part of manufacturing. But considering assembly early provides a different view of design and provides better designs that are easier to assemble, easier to make in modules, etc. What information is needed to support a rearranged design process in order to permit assembly to play these roles?

2. Integration of assembly into design would be made easier by the concept of "mating features" on parts. During design they can be taken from a standard database in many cases, together with their tolerances, fabrication process plans, and assembly instructions. These features are the information carriers for much of DFA as well as the starting point for a database of part mates, part interconnection lists, part-part tolerance propagation, and so on.

3. Typical machined, cast, and molded parts get their mating features during fabrication. Actual assembly on the shop floor consists of putting the mating features together. However, airframe parts obtain only a few mating features during fabrication. Assembly is accomplished by placing parts in fixtures and match-drilling and riveting by using still other fixtures. So, key points on the assembly fixtures play the role of most mating features. Thus even rough assembly planning of airframes must include data about the fixtures, something that is necessary only for very detailed planning of the assembly of other kinds of parts.

4. At the moment, airframe assembly planning and fixture design is not part of the early design process in most companies but is instead accomplished later by the tooling department. Neither the plan nor its dependent fixtures can be optimized by recourse to a different frame design (different module boundaries, for example). Concurrent Engineering would likely move that work upstream in the process. But placing those tooling designers directly in the path of early design decisions would require them to have access to data and algorithms that are presently unavailable. Existing assembly planning algorithms (all in research laboratories now) deal only with parts that have assembly features on them or that mate using recognizable surfaces on the parts. Fixtures that substitute for mating features are not part of assembly planning research. Formal assembly planning is not yet part of any ongoing product design process that I know of. No CAD databases contain information such as mating features and sequence algorithms that would support assembly planning.

The idea that a PDM is not simply a description of the product but must contain additional information *solely to support the design process* is a recent one. Because designers are still discovering the implications of Concurrent Engineering and the questions it raises, new information to support the design process will continue to be found.

I also strongly believe that the intellectual ferment in design today focuses squarely on this issue, not on the more traditional issues in design research, to which a great deal of attention is being paid. No one doubts that tolerances need to be represented, or that stresses need to be analyzed, or reliability predicted.

Furthermore, I think this issue is a showstopper. That is, if a satisfactory definition of product data does not emerge (allowing that it will evolve because technology advances and people get smarter), then design will continue to be more risky, experience-based, and inefficient than it needs to be, and major advances (e.g., totally new ways to use computers in design) simply will not happen, or will have restricted applicability.

Finally, I think this issue fills the requirements set forth at the beginning of this section. It is clear to me that

- this is a sharply defined question;
- basic knowledge about what constitutes design and engineering is needed to answer it;
- all the main players have clear and obvious roles to play in answering it;
- as answers come in, other research areas will be fostered (feature-based design, data compatibility, efficient change management, capture of engineering and physics knowledge, recognition of "similar" designs...); and
- progress will be easy to recognize and put to use as it emerges.

The current PDES/STEP activity is the first broadly based attack on this problem; it will not be the last. It must go forward because we need something we can test, react to, and use to formulate the next generation PDM.

A rough research plan for generating the next PDM is as follows:

1. Researchers should go to companies and obtain as many diverse detailed PDP examples as possible. The totality of issues recognized as being relevant to design, plus their interactions, should be collated and presented for comment. These issues will include questions asked of the design (what's a good assembly sequence?) as well as those asked of the design process itself (what's a good design decision sequence?).

2. From these PDP examples, a list of common design process questions or question types and their interactions should be drawn up, and alternative sequences for asking these questions listed. (It is already known that unique optimum sequences do not exist because many questions depend implicitly on each other, giving rise to iteration.[16]

3. If possible, discernible classes of design processes should be separated out for individual consideration. An obvious example is "redesign" of something whose basic architecture is the same as in past designs.

4. Each of the identified questions or question types from item 2 should be graded according to the long-term feasibility of answering it algorithmically and, if judged not feasible, then alternate methods should be identified. Naturally, judgments either way are subject to revision later.

5. At the same time, missing engineering knowledge that would help answer the questions should be identified. Any place where the method "expert system" is proposed under item 4 is a candidate for this category.

6. The data requirements for algorithms and engineering knowledge must be identified. For algorithms that do not yet exist, this is clearly not possible, but a rough description of the required information may be possible to construct.

7. A triage of the identified problems must be carried out and a priority list made so that individual attacks can be planned.

8. A requirements and capabilities list for the next generation PDM must then be drawn up, based on the priority list from item 7. A PDM capable of supporting existing algorithms is clearly the first target. In parallel, the most feasible algorithms should be developed. They must be scalable to the problem sizes found in the survey in item 1.

9. Demonstration projects must then be carried out to test the usefulness of the resulting PDM. The results of these projects must then be fed back into item 1 and the process repeated, taking account of the advances in technology and technique that have undoubtedly emerged during the cycle.

ACKNOWLEDGMENTS

I thank all the organizations and people I visited for their help, support, and hospitality. They worked hard for me and made my stay both educational and enjoyable.

REFERENCES

1. D.E. Whitney, "State of the Art in Japanese CAD Methodologies for Mechanical Products—Industrial Practice and University Research," *Office of Naval Research Far East Office Scientific Information Bulletin* **17**(1), 89-112 (1992).

2. D.E. Whitney, "Design-Build Teams at Aerospatiale," *ESNIB* **92-07**, 412-415 (1992).

3. D.E. Whitney, "System Design of Modular Products at Telemechanique," *ESNIB* **92-07**, 418-423 (1992).

4. D.E. Whitney, "Peugeot's Manufacturing Technology Challenges EC Assumptions," *ESNIB* **92-07**, 415-418 (1992).

5. D.E. Whitney, "From Geometric Modeling to Product Data Models: Collaboration Between Engineering, Computer Science, and Industry at Leeds University," *ESNIB* **92-07**, 406-411 (1992).

6. D.E. Whitney, "Perspectives on Artificial Intelligence in Design," *ESNIB* **92-07**, 391-396 (1992).

7. D.E. Whitney, "Design Research at Cranfield Institute of Technology," *ESNIB* **92-06**, 303-308 (1992).

8. I. Sherrin, G. Jared, M. Limage, and K. Swift, "Automated Manufacturability Evaluation," Cranfield Institute of Technology Working Paper, April 1991.

9. Michael French, *Form, Structure, and Mechanism* (MacMillan, London, 1992).

10. D.E. Whitney, "From Functional Specification to Concept Design—Strengths and Weaknesses in Some Current European Approaches," *ESNIB* **92-07**, 397-405 (1992).

11. W. Eversheim and M. Baumann, "Assembly-oriented Design Process," *Computers in Industry* **17**, 287-300 (1991).

12. G. Pahl and W. Beitz, *Engineering Design* (Springer-Verlag, Berlin, 1984).

13. H. Voelcker, "Modeling in the Design Process," in *Design and Analysis of Integrated Manufacturing Systems*, W. Dale Compton, ed. (National Academy Press, Washington, 1988), pp 167-199.

14. Marc Le Coq, "La R&D dans Une Logique Produit: Contribution a la Reduction des Delais de Conception," (R&D on Product-oriented Logic: A Contribution to Reducing Design Time), working paper, *Service Conception de Produits Nouveaux*, ENSAM, Paris, no date.

15 D.E. Whitney, "The U.K. Government Program in Engineering Design Research," *ESNIB* **92-05**, 250-254 (1992).

16. S.D. Eppinger, D.E. Whitney, R.P. Smith, and D.A. Gebala, "Organizing the Tasks in Complex Design Projects," in *Proceedings ASME Design Automation Conference: Design Theory and Methodology*, Chicago, Sept. 1990, Vol. DE-27, pp. 39-46.

Engineering

Dynamics and Control Research at the University of Manchester

by Alan M. Janiszewski, LTCOL, USAF, who is at the European Office of Aerospace Research and Development, where he is Technical Director and Chief for Structures and Structural Materials

KEYWORDS: collaborative efforts; nonlinear dynamics; monitoring; expert systems; optimization techniques

INTRODUCTION

At the suggestion of Dr. J. Olsen, Chief Scientist of the Flight Dynamics Directorate of the U.S. Air Force Wright Laboratory, Dayton, Ohio, I made a site visit to the Department of Engineering at the University of Manchester (UMIST), Manchester, U.K. The initial purpose was to meet with Dr. Otto Sensburg who is on sabbatical at UMIST from MBB (Messerschmitt-Bölkow-Blohm GmbH, the Military Aircraft Division of Deutsche Aerospace) in Munich. Dr. Sensburg is known to Dr. Olsen through participation in AGARD activities. I also met with Professor Geoffrey Tomlinson, Head of the Department of Engineering, and his staff and colleagues within the Department.

After a presentation on my part on the types of programs run by the European Office of Aerospace Research and Development (EOARD), I met with researchers in the Department's Dynamics and Control Research Group (DCRG). The DCRG spans a wide range of research topics and receives financial support from both U.K. and international companies, the U.K. defense industry, and other government agencies including the Science and Engineering Research Council (SERC). There is an increasing amount of collaboration with European academic/research institutions; these include LMS (Belgium), Politechnico di Torino and Fiat (Italy), DLR (Germany), and Shell U.K. Ltd. There is also joint research with NASA Langley (Virginia), and, as an immediate result of this visit, a new interaction with the Wright Laboratory. DCRG seems to be maximizing the benefit of working with researchers from other countries. The Group has eight major research topics currently active.

NONLINEAR SYSTEM IDENTIFICATION

This team, headed by Professor Tomlinson, is involved in efforts that parallel those of Dr. J. Hollkamp of the Flight Dynamics Directorate at the Wright Laboratory. (Dr. Hollkamp is a USAF 6.1 Task Manager in nonlinear dynamics and time domain analysis techniques.) The team at Manchester focuses on issues of:

- identification of structural nonlinearity using restoring surfaces;
- higher order frequency response functions in the analysis/identification of nonlinear structures;
- identification of shock absorber dynamics;
- dynamic loading of fluid-loading mechanisms;
- identification of aircraft structural nonlinearities; and
- time series methods using the NARMAX procedure.

LINEAR SYSTEM IDENTIFICATION

This team, headed by Drs. J.E. Cooper and J.R. Wright, works closely with the Nonlinear System Identification team and places emphasis on:

- development of methods to enable rapid flutter clearance of wind tunnel models and full-scale aircraft;

- development of force appropriation techniques (normal mode methods) for ground vibration testing of aircraft structures;
- expert system methodologies for aircraft ground vibration and flight testing;
- time domain system identification methods; and
- development of on-line system identification techniques.

ELASTOMERS/VISCOELASTIC MATERIALS

Dr. S.O. Oyadiji and Professor Tomlinson have had strong ties to the U.S. Air Force through collaboration with Dr. Lynn Rogers. (Dr. Rogers is retired from the Wright Laboratory, now serving as a consultant for the USAF and NASA. He is an internationally recognized expert in the general area of vibration suppression.) They now lead a team that is studying:

- viscoelastic material dynamic properties using Master Curve Methodologies;
- high and low frequency analysis of vibration isolators and mounts;
- evaluation of flexible pipe couplings and rolling lobe diaphragm seals; and
- applications of damping treatment to aero engine components

MAINTENANCE ENGINEERING/CONDITION MONITORING

A team that includes Dr. R.J. Wynne and two senior Engineering Lecturers focuses on issues related to manufacturing and manufacturing process technologies. Their major areas of interest/study include:

- condition-based maintenance for manufacturing;
- monitoring of robots for robotic production using vision systems;
- expert systems for fault diagnosis;
- neural networks for fault diagnosis;
- condition monitoring using laser vibrometry;
- diesel engine injector monitoring;
- electric current monitoring of three-phase motors; and
- characterization of the dynamic integrity of pavements.

MOTORCYCLE INTERNAL COMBUSTION ENGINES

This effort, headed by Dr. G.R. Roe, is studying the special problems of:

- stability, handling, and development of new chassis designs for motorcycles; and
- dynamics and silencing of internal combustion engines.

SIMULATION AND CONTROL OF INDUSTRIAL PROCESSES

Dr. C. Tye leads an effort involved with the assessment of:

- simulation and control of dynamic systems by using expert systems and parallel processing; and
- self-adapting and self-tuning control systems.

CONTROL

Dr. R.J. Wynne and his team have been identified through this site visit to begin a feasibility study for the U.S. Air Force (Vehicle Subsystems Division of the Flight Dynamics Directorate) to use piezoelectric film to "actively" control a constrained viscoelastic damping layer. This active/passive approach is thought to have potential for vibration suppression of avionics equipment. One of Dr. Wynne's Ph.D. students will be traveling to the U.S. under EOARD's Window on Science program to coordinate this research with in-house efforts of the Structure Division at the Flight Dynamics Directorate. In addition to these activities, the control team's efforts include:

- development of a qualitative controller for process control;

- evaluation of robust control design techniques;
- automation of extrusion processes;
- artificial intelligence techniques in process control and flow measurement; and
- optimal multivariable control with actuation and measurement constraints

BIO-MEDICAL ENGINEERING

Dr. D. Ball heads this DCRG team, which is pursuing research related to:

- quantification of hand tremor related to Parkinsons disease and cerebella disorders;
- investigation of joint stiffness symptoms;
- development of measurement systems for general practitioner and hospital use; and
- research into the dynamics of muscle-reflex action.

FUNDING

Also noteworthy is the broad list of supporters to this research. Funding sources include such diverse activities as: BAe (both Airlines and Airbus Divisions); British Council; Ford Motor Company; British Petroleum (BP); Metalastic; BRITE-EURAM; Predictive Control; Department of Energy; Rolls-Royce; Shell U.K. Ltd.; Fiat; and numerous others.

EQUIPMENT

In addition to a highly qualified staff of researchers and technicians, the Department has fairly extensive computing and experimental facilities (at least by university standards). In most cases this is the result of external funding from industry. The DCRG carries out vibration testing and analysis on a variety of equipment, including HP 9000 computers with LMS test and analysis software, a VAX 3100 workstation, several SUN workstations, DIFA 12- and 48-channel input/output analyzers, 386 and 486 personal computers, and associated test hardware (amplifiers, accelerometers, force gauges, etc).

The computers are linked via the Ethernet network to provide access to other systems, which facilitates use of CAD, MATLAB, and FEM packages. The motorcycle team has dynamometers and noise measurement and analysis instrumentation.

DYNAMICS TESTING AGENCY (DTA)

The DTA is a newly formed industrial club that has been set up to develop independent quality-assurance standards in engineering testing, measurement, and data analysis in structural dynamics. Members of the DCRG are active participants in the DTA.

ACTIVITIES

The Dynamics and Control Research Group at the University of Manchester is very active in giving short courses to and within industry. Recent courses include:

- Dynamic Testing of Materials
- Signal Processing for Engineers
- Vibration Analysis and ID for Linear and Nonlinear Structures
- Introduction to Structural Dynamics and Aeroelasticity
- Signal Processing and Structural Dynamics Test Methods with Application to Aircraft Ground Vibration and Flight Flutter Testing
- Introduction to the Analysis of Dynamic Test Data.

Dr. Sensburg has broad experience in the application of mathematical optimization methods to aircraft design. His work parallels some of the work of Dr. V. Venkayya of the Wright Laboratory. Dr. Venkayya visited Dr. Sensburg and Prof. Tomlinson at the University in June 1992. They shared perspectives on structural optimization techniques and the challenges facing them. A possible concurrent study of the same structural optimization problem (an aircraft problem) by using MMB's codes and those developed by Dr. Venkayya at the Wright Laboratory was proposed;

a no-cost comparison was seen to be of value to both organizations. The details of this collaboration are to be worked out this summer when Dr. Sensburg visits the Wright Laboratory.

The Dynamics and Control Centre at the University of Manchester is doing excellent work incorrelating theoretical and experimental advances in each of the specific areas highlighted in this report.

Point of Contact

Professor Geoffrey Tomlinson
University of Manchester
Department of Engineering
Simon Building
Oxford Road
Manchester M13, 9PL
United Kingdom
Phone: 44 61-275-4444

Manufacturing

New CAD Software from Dassault Systems: Starting to Combine Design and Engineering

by Daniel E. Whitney, formerly Liaison Scientist for Manufacturing at the Office of Naval Research European Office. Dr. Whitney is at the Charles Stark Draper Laboratory, Inc., Cambridge, MA.

KEYWORDS: CATIA; long-term strategy; geometric modeler; infrastructure; engineering design support

SUMMARY

This article describes recent developments and prototype software that will extend the range of the three-dimensional (3D) modeler CATIA. CATIA started out as an aerospace industry product but recently has made major inroads in the car industry. New software plans include providing object-oriented databases; using free-form 3D sketchers; providing the ability to manipulate constraints, engineering equations, and tolerances; and modeling assembly processes. A new and quite large European Strategic Programme for Research and Development in Information Technology (ESPRIT) project on assembly has just begun. It's a turning point in computer-aided design (CAD) capabilities.

GENERAL BACKGROUND

Dassault Systemes (DS) is one of the major suppliers of CAD/CAM (computer-aided manufacturing) software. It was founded in 1981 as an offshoot of Dassault Aircraft and has grown from 15 employees then to 1000 today. Annual sales are usually about FF 1 million per employee, year after year. Several years ago, DS formed a broad strategic alliance with IBM—selling it a minority interest, buying CADAM (a 2D CAD package) from it, and obtaining marketing, software, hardware, and maintenance services world-wide. As a result, DS is well supported with the means to write and sell CAD/CAM software on both workstations and mainframes.

Their major product is a 3D modeler called CATIA, which originated in Dassault Aircraft. A practical results is that, unlike most other CAD vendors, DS's evolution has been from 3D to 2D, rather than the reverse. In the past, when CATIA was DS's only product, DS's capabilities were strong in surface modeling (suitable for aircraft) but weak in conventional 2D drafting and solid modeling (suitable for automobile engines); again, this is the reverse of many CAD vendors. These differences are gradually being corrected by the purchase of CADAM and the addition of 3D solid modeling to CATIA. Among the improvements

are those aimed at enabling a designer to convert a fully dimensioned and toleranced 3D design into conventional 2D drawings for transfer to manufacturing.

CATIA currently consists of about 5 million lines of FORTRAN comprising the geometric modeler and an infrastructure of data management and other facilities. In addition to this infrastructure, there are an additional 8 million lines of applications code (apps) and other infrastructure. The apps include various CAE software (finite-element codes, kinematic analyses, the beginnings of tolerance representations, etc.) plus communications capabilities to make concurrent engineering easier. The infrastructure makes it easier for third-party developers to insert and check their own applications. Apparently much of this development has been driven by the customers. "It's pretty hard to keep up with them," says Dominique Florack, Manager of R&D Strategy.

Another technique for strengthening DS has been to hire people from engineering organizations, including Dassault Aircraft, so that new developments will be more focused on the needs of current and new customers.

DS is also interesting in the way it develops new capabilities. According to Florack, half of their internal R&D projects are co-funded with one or more industrial partners. These partners will have a two-year exclusive opportunity to use the results before they are sold generally.

DS now has 3000 customers representing more than 19000 seats, with twice as many seats being mainframe-driven as workstation-driven. The customers are distributed as follows:

- 50 percent Europe, 25 percent U.S., 25 percent Asia;
- 40 percent automobile, 30 percent aerospace, 30 percent other.

Recent and well-publicized sales have been to Boeing, for the 777 program, and Chrysler, which adopted an "all CATIA" strategy about two years ago. The sale to Boeing has blocked DS from selling to Aerospatiale, but the sale to Chrysler has not blocked sales to German car companies. Here, another national style difference emerges: the German car companies are working together on several fronts, including standardizing databases for dealing with suppliers' CAD systems. Cooperation at this level, including using the same design software, is deemed important for survival of their industry. (See next report about Volvo and Volkswagen.) Finally, DS has made headway with the engineering services industry, notably Bechtel, a designer/builder of nuclear power plants, oil refineries, and public works projects. CAD/CAE for these customers includes piping layout, buildings, steel structure, and so on.

Other regional differences affect DS's long-term strategy. The U.S. customers are demanding an open architecture, presumably because they hope to add applications from other vendors. They also think that openness will help them overcome incompatibilities between data formats in different programs, permitting them to keep more of their installed base of older software. Boeing and Japanese customers are starting to ask for shared screens—the ability for two or more designers to work on the same design at the same time. (This contradicts my finding a year ago that the Japanese are not looking forward to substituting computer communication for face-to-face communication.) The Japanese are also asking for open architecture, but so they can add their own software rather than that of other vendors. (This is consistent with my finding that each Japanese company wants to tailor its CAD software to its distinctive "working style.")

The new capabilities DS is adding comprise the maturing of a drawing package into an engineering and enterprise management package, a trend ongoing at other CAD companies as well. This is stretching DS as well as the old software technology on which CATIA is based. Gradually FORTRAN is being replaced by C, but DS would rather use C++ because of its object-orientation. O-O is seen as vital for more powerful databases, groupwork, versioning, event notification, and other aspects of highly interactive and integrated engineering. Unfortunately, there is no C++ standard for workstations and no C++ at all for mainframes. Object-orientation is not the answer to everything either—it's too slow in many applications—so it is not clear how CATIA and other CAD products will evolve over the next few years.

NEW DEVELOPMENTS

Pascal Lecland, Manager of New Technologies and Research, and several of his staff discussed and demonstrated new projects that will ultimately appear as CATIA capabilities:

- a free-form design sketcher for solid objects
- representation of constraints and parameterization in engineering design
- representation of tolerances
- the ESPRIT-funded SCOPES project in assembly modeling.

These are discussed in turn. They are interesting in part because they represent topics that are being worked on at several university research laboratories. Either technology transfer is starting to happen very rapidly, or the universities are not very far ahead of some applications. Both may be partly true, and in some cases I think the universities are behind. In others, DS's capabilities will be quite modest in these areas at first.

Free-form Design Sketcher

This project was described by David Bonner, a recent Massachusetts Institute of Technology (MIT) graduate and new hire. Bonner developed the sketcher as his Master of Science thesis under Professor Mark Jakeila of the MIT Mechanical Engineering Department. The research was originally sponsored by Nissan. The sketcher permits one to input a solid elongated shape and then distort it systematically into a desired shape. Both large- and small-scale deformations are possible. The object maintains certain shape constraints while deforming, such as keeping slope or second derivatives continuous everywhere, and keeping the surface closed.

Extensions Bonner is working on for DS include the ability to tie the shape to certain curves imbedded in the surface (what the car designers call feature lines) and then cause the surface to deform when these curves are deformed. So far, no attempt has been made to relate the surface deformations to explicitly written constraints (keep the volume = 500, make the left end half the diameter of the right end, etc.)

(Although Bonner and Lecland said that no other modeler could presently do what this one does, I saw a similar capability at Volvo. The software is called ALIAS, whose surfaces are built on Bezier curves. The designer can pull on a curve and the whole surface will deform smoothly. In this way, Volvo has converted several of its clay model car stylists into computer-based stylists. Compare this to Toyota's method of having a computer person attempt to convert stylists' sketches, then sit with the stylist and correct the model.)

Representation of Constraints

The goal here is to improve the ability of CATIA to support engineering, as distinct from drawing. This project and SCOPES (below) represent major departures from typical CAD. I believe the constraints project is just beginning, although such work has been ongoing at several universities for some time.

The basic issue is to find a good design for a problem that is primarily defined by sets of simultaneous nonlinear equations and inequality constraints, some of whose parameters also define geometry in a solid model. General solution methods do not exist, and DS is not trying to find such solutions. A multi-prong attack is being used, comprising elements of artificial intelligence (AI), mathematical programming, constraint propagation, and numerical solutions.

The AI approach appears to be rule-based and similar to ICAD.[1] The math programming approach is hard to generalize since such algorithms typically must be carefully constructed specifically for each problem. For the time being, Lecland appears satisfied to present the designer with a family of solutions obtained any way possible, including successive numerical search, and let the designer choose.

Three possible applications/illustrations were given:

1. 2D and 3D equipment layout to meet constraints. For example, place machines on a factory floor or so that trip distances between them along typical process routes are shortest. (Several classic operations research or mathematical programming approaches to this problem exist; some AI methods have also been tried.)

2. Advise designers on selecting equipment or parts from catalogs to meet constraints presented by the designer or the design. The goal is to support "fuzzy requests," presumably avoiding the need to describe the needed item explicitly. (Two forms of this problem have been identified. One selects single items, which is not too hard. The other tries to select sets of items that will be connected to each other. This is a lot harder. Allen Ward at the University of Michigan did his Ph.D. thesis work on this.)

3. Study the problem of allocating space, such as between the front wheels of a front-wheel drive car. (This is a striking coincidence, since I use this very example in speaking about how Japanese car companies organize design projects. This allocation is a crucial one; the way different companies deal with it says a lot about how the companies organize their design processes.) The approach suggested by Lecland was to vary the parameters systematically, redrawing the layout in real time so that the designer can see a lot of alternatives one after another.

For the long term, he envisions a "full concurrent design approach" that combines freeform sketching and constraint-based design.

Features and Tolerances for Parts and Assemblies

This was described by Philippe Dufosse. DS is working on these topics at several levels, not only upgrading existing software but also developing new capabilities. These were described and shown as prototype demonstrations later in the day.

Dufosse divided the topic into mechanical design modeling (kinematics), assembly modeling, assembly process design, and tolerancing of both parts and assemblies.

He described and then demonstrated a 3D mechanism sketcher based on features. The features supported are plane faces, cylinders, and cylindrical holes. One can sketch simple solid shapes and link them with the features. Plane faces can be placed against each other. Cylinders can be located on the object via the object's coordinate frame and some simple commands. Cylinders and holes can be aligned via their centerlines; the surface contact between peg and hole is then detected automatically and the kinematic degrees of freedom are noted in the model. When the model is finished (here a simple slider-crank mechanism), it can be animated. The designer deals at the level of shapes and mutual constraints between them. The design is unscaled, and the designer can add actual dimensions later.

Assembly modeling is going on at two levels. One level merely places parts on the computer screen in the correct mutual locations. This creates a data model that tells what parts are present and where they are. The other level models (actually will model when the SCOPES project is done) the processes by which assembly would occur in the factory. This model is hierarchical in that it defines subassemblies recursively; the minimal subassembly has one part.

A nearer-term use for assembly modeling will be to allow designers to access catalog parts and place them correctly in a design along with drawn parts. Another potential use is to search for existing designs described somehow (types of parts in them?). This was not clear but is obviously useful and not easy to accomplish.

Functional dimensioning and tolerancing is also going on at several levels. For single parts, the goal is to provide enough information to program coordinate measuring machines and compare the results to the design. Current methods of assigning tolerances in CAD usually mean adding some text annotations to 2D drafting. There is little connection to the geometry itself. Lots of errors are made, every designer assigns tolerance types and values his own way, and the design can't be checked.

The new approach is based on work by Professor Andre Clement, who has developed a conceptual model of tolerancing based on kinematic concepts.[2] A tolerance describes or constrains one or more kinematic degrees of freedom, such as a point, a line and a point, and so on. These are called geometric reference elements (GRE). If a hole is to be located relative to two surfaces, the constraints involved are two planes and a line. Such constraints are added directly to a 3D model.

At present, the related surfaces must be identified by the designer; although I got the impression that DS thinks this can be done automatically, I am not sure how they will do it. A possible way is to look at the surfaces as part of named engineering items like "bearing seat." Standard ways of dimensioning and tolerancing such items could be stored in a database. So far they are not taking this approach.

In the demonstration, I saw what they are doing now. A user makes a fully surfaced model and then begins to associate surfaces. For example, a part that will hold a caster wheel has two cylindrical bearing surfaces on a shaft and a flat face at the root of the shaft. The designer wants the first cylinder perpendicular to the face, so he clicks on these two surfaces and clicks on "perpendicular" in a menu. The software offers several choices for geometric dimensioning and tolerancing notations, from which the designer chooses one. He then fills in the numbers representing the degree of perpendicularity he wants. Similarly, he makes the two cylindrical surfaces concentric. When this process is complete, the designer can ask that a three-view conventional 2D drawing be made, containing all the tolerances and dimensions in the right places.

Next year they plan to extend this capability, exploiting the fact that the GREs provide a way to relate the dimensioned and toleranced surfaces to each other systematically. Possible extensions include computing tolerance chains by both worst-case and statistical methods to check for the possibility that parts will not fit; synthesizing tolerances based on minimum cost; and understanding how tolerances propagate through assemblies of parts. Over-dimensioned parts and inconsistent tolerances may also be possible to detect.

Professor Clement observes that all of the surface selection done by the user now could be done automatically by using his methods. He feels this might be necessary because so few designers really understand tolerances—how to select the right surfaces, or how to choose the numerical values for the tolerances.

In my opinion, such automatic selection and numerical assignment cannot be done until the engineering content of the geometry is captured by calling it a bearing seat, for example, and referring to a database for additional information about bearing seats. This approach will work as long as design consists of reusing old things or basing new ones on defined concepts. But not every concave cutout in a part is destined for an established and documented use. Thus higher level descriptions are also needed, such as "capture a substantially rigid convex shape and hold it against forces and torques of XX magnitude in the YY and ZZ directions."

The SCOPES Assembly Modeling Project

Boubker Badr, DS's program manager for the SCOPES project, described it. This 3-year, 67.7 man-year project sponsored by ESPRIT III is just getting started. The partners are DS, Telemechanique, Mandelli, and four research laboratories, including the CIM Institute at Cranfield. Telemechanique[3] is a French company that builds industrial controls for automation systems as well as automation systems themselves. Mandelli is an Italian machine tool and automation systems builder.

The main structure of the project is divided into two parts:

- the "offline design" of a multipart product and creation of the assembly plan for it, including concept design of the assembly plant; and
- the "online design" of the details of the factory and its real-time control system.

DS is the task leader for the offline part while Telemechanique leads the online part. Both Telemechanique and Mandelli will be user test sites during the project. A planned demonstration will consist of designing a product and a robot assembly cell for assembling it, then designing the control system for the cell, then building and operating the cell at Telemechanique's research and development laboratory. No software will be delivered as part of the project. Instead, DS will judge the success and usefulness of any software it develops and decide later if it will be added to CATIA.

This project, as stated above, represents a totally new direction for CAD. Assembly is the first really new CAD/CAM application since numerical control, and assembly brings totally new issues to the surface. Among these are

- dealing with several parts at once;
- understanding all the ways those parts will interact;
- exploiting the integrative character of assembly to help tie the design process together; and
- understanding assembly as both a process that occurs in the factory and as a way that parts provide "engineering services" to each other (support, location, sealing, heat transfer, retain fluid...) and then connecting those "services" to the assembly constraints inherent in individual part mates (slide in, fit against, glue together, fasten with screw, compress O-ring,...).

In more detail, the project has three segments: offline, online, and the offline-online interface. These are described briefly below:

Offline

This will consist of three activities, namely product redesign or design for assembly (DFA), assembly planning, and resource planning.

Redesign will actually involve the designer using conventional DFA rules and other criteria such as properties of different assembly sequences iteratively to arrive at a suitable design.

Assembly planning, part of the above iteration, will consist of generating the possible assembly sequences for the product based on geometric properties of the CATIA model, and evaluating them according to criteria such as the ability to support model variants of the product, least use of fixtures and tools, and management of subassemblies. These criteria are similar to those being investigated in the assembly planning research community,[4] and techniques from research laboratories will be used.

Resource planning will consist of identifying "logical" resources such as generic tools, people, or robots that are described parametrically by size, speed, or load capacity. These will be matched to the required assembly sequence by methods not made clear to me. However, researchers have created some applicable methods. These logical resources will be laid out on a factory floor while obeying facility constraints such as avoiding pillars and minimizing flow path lengths.

Significantly, the project does not include estimating assembly cost. In my opinion, resource planning depends crucially on resource cost and speed, so cost is not separable from resource planning. Fabrication cost is also absent, yet it is well known that redesign based on DFA criteria sometimes increases the cost of parts. A more complete design system would therefore permit these important tradeoffs to be evaluated.

Offline/online Interface

This part of the project will be jointly managed by DS and Telemechanique. Its main component will be a detailed but conventional discrete event simulation of the planned assembly system. The issues to be explored in this interface are scheduling the system, controlling material flow, and recovering from errors. The simulation will exist at three levels of detail: each workstation, cells of several stations, and the whole assembly system.

Online

In this part of the project, the system will be designed and built. In particular, the system control software, communication links, sensors, monitoring, user interface, diagnostics and error recovery, scheduling, and statistical quality control will all be specified, designed, built, and tested. Control, scheduling, and error recovery algorithms derived during the simulation phase will be used, and the operation of the actual system will be monitored by the simulation. Methods for designing these system elements will presumably be developed, but I have no information about this.

This is obviously an ambitious and important project, perhaps too big for the time allowed. It will not directly address the larger issues listed above but it will open the way for such issues to be addressed in parallel or in the future.

Software Demonstrations

In addition to the demonstrations of kinematic sketching and tolerancing described above, I saw one on a prototype for a new mouse-menu-icon user interface that included shared screens and other support for concurrent engineering. This

system is based on a version of X Windows called XCAD. As such, it supports multitasking, which in this case means supporting several CATIA applications running at the same time on the same or different geometric models.

Several features are supported. The simplest permits a user to send a model to another user, although not yet by simply clicking on an icon that represents that user. The next permits a user to launch a CATIA application by dragging the icon for the model onto the icon for CATIA. This act launches a message from one data object (the model) to another object (CATIA), causing an instance of CATIA to be created to run that model. The third facility keeps a journal of all the designer's actions (a little recording tape icon) that can be replayed later or used to create a variant of the model.

The last and most ambitious capability is groupwork. This permits several levels of cooperative work. The lowest level permits a user to look over the shoulder of another user. The next permits him to launch a CATIA instance on the other person's screen. The highest permits both to modify the same model "at the same time" in the sense that either one can modify it without asking permission from the other. This is called "debate mode." I think DS recognizes the need to reconcile databases that result from two or more designers working on the same model, but no mechanism has been identified for doing so. This is a potential showstopper for groupwork, and several researchers are studying it.

CONCLUSIONS

DS is moving CATIA from a geometry modeler to an engineering design support system. It appears to be actively seeking recent research results, not only by following the literature but also by hiring recent graduates who have done such research. At present CATIA is still primarily geometry-oriented, and the hard engineering capabilities have only recently been considered. But this is the long-term trend, and other CAD companies are moving in the same direction.

The kinds of research that DS and other CAD vendors' work still need include

- better and faster databases for managing really large and complex designs;
- object-oriented (or other content-driven) approaches for manipulating design data and relating geometry to engineering;
- better user interfaces for creating and manipulating solid models;
- ways of modeling design processes so that CAD systems can help companies create and optimize such processes as well as manage them; and
- more understanding of assembly processes and their relation to engineering: both the engineering of the assembly actions themselves and the assembly implications/ descriptions of engineering functions accomplished by groups of parts

REFERENCES

1. D.E. Whitney, "Design Research at Cranfield Institute of Technology," *ESNIB* **92-06**, 303-308 (1992).
2. M. Briard, B. Charles, A. Clement, P. Pelissou, and A. Riviere, "The Mating Function in CAD/CAM Systems," presented at the ASME Design Automation Conference, Montreal, September, 1989.
3. D.E. Whitney, "System Design of Modular Products at Telemechanique," *ESNIB* **92-07**, 418-423 (1992).
4. D.E. Whitney, "Robotics in Theory, Robotics in Practice: 1992 IEEE Robotics and Automation Conference," *ESNIB* **92-05**, 241-249 (1992).

Points of Contact

M. Bernard Charles, Executive Vice President
Phone: 33 1 40 99 40 40

Professor Andre Clement, Scientific Advisor
Phone: 33 1 40 99 40 41

M. Dominique Florack, Manager, R&D Strategy
Phone: 33 1 40 99 40 34

M. Pascal Lecland, Manager, New Technologies and Research
Phone: 33 1 40 99 41 62

all at 24-28 Ave du General de Gaulle - BP 310
92156 Suresnes Cedex, France

Fax: 33 1 40 99 42 96

Dramatic Reductions in Lead Time at Volvo Based on Restructuring the Design Process and Introducing the Computer

by Daniel E. Whitney, who was the Liaison Scientist for Manufacturing at the Office of Naval Research European Office. Dr. Whitney is at the Charles Stark Draper Laboratory, Inc., Cambridge, MA.

KEYWORDS: design process; manufacturing engineering; prototype production; automation; Integrated Engineering

SUMMARY

For a relatively small company, Volvo has made substantial progress in design technology. In some areas, such as centralized design-development and paperless design processes, Volvo is on a par with some Japanese companies and ahead of some European and American rivals. They are keenly aware that design is a process just like typical manufacturing processes. Like manufacturing processes, design processes must be studied, rearranged, analyzed for their pacing operations and required information, and redesigned for greater efficiency and higher quality output. Volvo is also the first place I have visited where there is an appreciation for the fact that conflict is an essential part of design, not a symptom that people can't get along.

BACKGROUND

Volvo was founded in 1927 and today has about 30,000 employees. In 1989 it sold more than 400,000 cars; in 1991 about 310,000 were sold. [It's amazing for an outsider to note the small population of countries such as Sweden and Belgium (8.6 million and 3 million, respectively). If the ratio of the U.S. population to that is Sweden is multiplied by the size of Volvo, one gets 924,000—more than all the U.S. car builders combined! Thus proportionately, Sweden's car industry is bigger than ours. In addition, Sweden has Saab, ASEA, Thyssen, SKF, and other fine engineering companies.] Most of its production capacity is in Sweden, but there are plants in Belgium, The Netherlands, and Canada. About 2600 employees work in engineering, design, and development.

Volvo has been a pioneer in car safety and in car assembly methods. Among its most interesting plants is one at Uddevalla that has teams of people who assemble an entire car. At both Uddevalla and Kalmar the cars are carried by automatic guided vehicles (AGVs) rather than by conventional moving conveyor lines. But both of these plants produce relatively few cars per year, about 18000. The big plant at Gothenburg makes five times as many by using a conventional line arrangement. Their most productive plant is in fact the one in Ghent, whose output is about the same as Gothenburg's.

The question of whether teams or lines are better is not really the subject of my visit or of my European study in general, but it is interesting because it has implications for design and manufacturing in general. Henry Ford used teams in the early 1900s and found that the workers spent too much time fetching parts. Even walking a few feet takes too long. The moving assembly line was the solution. At Volvo, lines caused high absenteeism and employee turnover. [They did the same at Ford. This is apparently why Ford raised its wage to $5 per day in 1914, an unheard-of and revolutionary action. It launched the U.S. as a high-wage manufacturing country, a fact that benefitted millions of people for decade but is hurting us now as we try to compete against other newly emerging nations.]

Several solutions have been tried, including one team per car (Uddevalla) and one team per system, such as exhaust or electrical (Kalmar). Both suffer from lost time due to errors because

each person must remember many operations or look up instructions. By Volvo's own experiments, actual assembly time for one of their cars is less than 18 man-hours. However, in the factory this takes 30 to 40 due man-hours as the result of logistics and rework overhead. Lines are better in this respect.

However, lines are difficult to use when several car models must be made at once in unpredictable ratios. Volvc does not capitalize on its freedom from this restriction in its non-line plants because each plant makes one model. Nissan seems to be ahead in using non-line arrangements with AGVs to make many models in what is coming to be called "lean-flexible" or "agile" production. Few U.S. companies have tried this. It is not clear what the implications for design are, although my past visits to Nippondenso and Telemechanique have shown that design can play a big role in improving the producibility of high-variety products that have only a few parts (less than 100, say). Volvo will have to learn agile production and give up some old habits, said one of my hosts. One of the new challenges is how to be flexible without being more costly. Right now, no one believes it is possible.

OUTLINE OF THE IDEAL CAR DESIGN PROCESS

My host, Kurt Larsson (General Manager of Computer-Integrated Manufacturing) explained the process they are moving toward. Design and development take place at the central facility in Gothenburg. Here, stylists, engineers, production engineers, and the prototype manufacturing facility are located together, a development that only some Japanese companies and Chrysler have achieved. Car development is based on forming project teams with a single design manager; this process has been used in various forms for nearly 10 years. At present, the design manager does not have full budgetary control, so his power is less than it should be. Also, there are too many extra "helpers" on each project. Finally, complete paperless data flows have not yet been achieved.

Concept Design

With these caveats, here is the process. It is based on "keeping control of the whole vehicle" as one data package and set of design tasks. First, there is the typical process by which concepts are produced and evaluated. As described by Per Isaksson, it is surprisingly well-integrated in software, perhaps as well as at Toyota. (Starting in the 1970s, Volvo was one of the first car companies to integrate styling and engineering, says Dan Ahlen, whose historical perspective is given later in the report.) This integration includes combining styling with aerodynamic studies, crash simulation, stress analysis, quality and fitup, interior design, and manufacturing planning. All of the output is fully CATIA-compatible, and Volvo is gradually standardizing on CATIA for its CAD/CAM (computer-aided design/computer-aided manufacturing).

In one sense, Volvo's concept design process is more computerized than Toyota's since stylists can work directly on the computer rather than with clay, although only three do it so far. The software being used for this is called ALIAS, made and sold by people who spun off from Silicon Graphics. It makes surfaces from Bezier polynomials; the stylist can deform the surface freely by grasping control points on it. A stylist demonstrated this for me with a model of a car seat. (Note that this "same" capability is the subject of research at the Massachusetts Institute of Technology (MIT) and is called "new to CAD" by Dassault Systemes. I do not know whether I am missing an important point here or whether research is not as far ahead as researchers think.) ALIAS is fully compatible with CATIA.

I asked the stylist what it was like to use this method. I wondered aloud if working with clay was primarily a hand-oriented effort that did not carry over into the CAD environment. (For example, would some virtual reality help him, though I did not ask him this.) He replied that he felt styling was primarily a matter of eyes, not hands, even if the output was a clay model. So when the output is a computer drawing, he apparently is quite at home.

Larsson pointed out that CATIA can be used to cut the stamping dies from the surface model, but CATIA does not help with the rest of die design (such as the clamps or analyses of formability). The closed nature of CATIA has kept Volvo from adding such software itself. Toyota's solution (write their own from scratch to do all these tasks) is too costly for Volvo.

Volvo is able to exchange concept design data with its studio in Los Angeles. Designs can be made there, sent to Gothenburg for milling into clay models, and critiques can be sent back electronically to Los Angeles.

Detail Design

After the concept is approved, detail design begins. This is a much more disciplined process than concept design. The full dataset is parceled out as individual part models and packaging tasks (grouping parts into relationships with each other, such as under-the-hood). Part models are designed in detail, while packaging studies are done by manufacturing and assembly people who simulate their processes. These people also produce soft tooling, which is capable of making only prototypes but otherwise quite accurate, from which trial cars are built and crash tested. When these cars are assembled, "no hammers are allowed," meaning that every assembly problem is recorded on the CAD model. These results, as well as crash test results, are fed back into the master database and the design is improved.

Thus technology enables a social problem to be solved along with a technical problem. The social problem is that people do not recognize the information value of mistakes, so they try to hide them. The technical problem is that people think the prototype assembly process is supposed to find errors in the tooling, whereas the real purpose is to find errors in the design. Keeping control of the data all the way around the design-prototype-error-reporting loop is essential for solving both problems.

Side Comment

Larsson would like to extend the process of recording problems into the CAD database to the factory floor because the employees have so much untapped knowledge about design problems. "First, we have to turn the company upside down so that the workers are on top. Then we have to facilitize them with terminals. Right now secretaries have terminals. Once the workers have them we could take advantage of multimedia computing and give them little TV cameras and microphones. They could document their problems directly into the database where designers could see them very vividly."

This is a great idea and it has research implications, too, because the problems must be linked to the right places in the design data. How are those places to be found? The issue is larger than finding the design of the part that is in the TV picture, because a diagnosis must be made. It is likely that the part in the picture is not the one causing the problem. It takes a lot of knowledge to decide where the culprit is, and why (a process out of control, a supplier whose parts or materials have drifted out of spec...). So, again, we find that a product data model must have information links in it that say what affects what, under what circumstances.

Final Tooling Design

Outside the prototype verification loop is the final design of the factory and its equipment. Fixture design is done by using numerical models of the parts so that they will fit together. This is also done if the machines and fixtures are to be bought from outside suppliers. It is not clear what percentage of all final tooling and factory design is done by computer, but the fraction is rising.

Numerical data are also used in ordering many of the parts from outside. To support this process, Volvo has established a computer department equipped with data translators that will convert CATIA to many formats compatible with the suppliers' CAD systems. Volvo is also an invited partner in the German car industry's supplier data standardization project (see "Electromechanical Design in Europe: University Research and Industrial Practice," *ESNIB*, this issue). A chart shown by Mikael Diedrichs indicated the size of data traffic now going on: starting in 1987, Volvo sent out about 2000 CAD models per year by using disks and tapes; today the number is 12,000 and rising rapidly. Such models are typically 0.5 to

1.5 megabytes each. (In the same time period, says Diedrichs, BMW's traffic rose from 2000 to more than 40,000 models!) Starting in mid-1990, direct telephone data transmission has begun using the X25/OFTP protocol. This European standard is being tested by Volvo and six of its suppliers. About 4000 CAD models per year are sent this way.

The shortcomings of CATIA limit the amount of factory simulation Volvo can do. For example, robots can be programmed from part data to spray paint but not to weld car bodies. Other software is used for that. Also, CATIA cannot hold large solid models of many parts so that interference checks (part-to-part, part-to-robot, etc.) can be done. The Japanese I visited said the same thing.

However, CATIA's firm solid model permits Volvo to use data conversion and communication with suppliers with confidence, whereas they have no such confidence in converting ordinary two-dimensional (2D) models made by drafting software. This shows that mathematical research efforts to create logically consistent three-dimensional (3D) models have paid off in a serious way. CATIA's historical evolution from 3D to 2D (see "New CAD Software from Dassault Systemes," *ESNIB*, this issue) may put it in a good position to solve the 2D conversion-transmission problem.

Altogether, they estimate that the use of CAD and numerical control has cut body engineering time by 50 percent. They are now turning their attention to power train design, namely engines and transmissions. This is discussed below.

ORIGIN AND MATURING OF VOLVO'S CURRENT PRODUCT DESIGN METHODOLOGY

According to Dan Ahlen, Volvo started CAD in body engineering in the early 1970s; by 1980 all body engineering was being done by computer, using a mix of commercial and in-house software. This has enabled Volvo to carry on several vital engineering activities in parallel rather than in series. One of these is checking that the separately designed panels fit together properly. This used to be done in a model shop. When the shop was satisfied, it built wood patterns from which stamping dies were made by copy-milling machines. The shop had all the "information" and thus tended to run the entire design process. The process stepped ahead when the shop released its information and not before. When numerical control took over, an important power shift in the organization occurred, not without some problems on the way. Volvo still views the design process as a matter of establishing, freezing, and releasing datasets.

The process of fitting up has also matured from pair-wise checks to a hierarchical check. For example, the size, shape, and tolerances of doors are driven by corresponding data for the door opening. This sort of thing cannot yet be done in power train design because that department still uses 2D drafting software.

Volvo also still struggles with the problem of individual power centers that do not see "the whole vehicle," a way of saying that implementing concurrent engineering is difficult. Most companies encounter similar problems: the product is complex and is thus divided into subsystems to reduce complexity and focus expertise on individual areas and technologies. Each subsystem used to be designed by its own organization, leading to a great deal of conflict as each group tried to optimize its system. Volvo has gradually converted from this departmental structure to a project structure, but the old problems still remain to some extent because the project leader does not have complete control.

THE INTEGRATED ENGINEERING APPROACH

The process of maturing the power train (and chassis) designs appears to be following a more deliberate path than does body engineering. Perhaps the participants learned from their 1970s experience. Perhaps body engineering is not as complex. In any case, Ahlen and Larsson have given the process a name: Integrated Engineering. They also have developed a procedure for accomplishing it and have tried it out on some individual parts. Now they are in the process of trying it on entire engines. For this purpose, Larsson's department has taken on the responsibility for modeling design processes, redesigning the processes, and proving to the designers that they can cut 50 percent or more from the time they currently take.

The main problem they face is demonstrating to people, management, and engineers that design

contains inherent conflicts. When one person "improves" his part of the design, it can hurt some other part. When such "improvements" are factored into the design, or when problems with fabrication or assembly are discovered, changes must be made. The resulting revisions slosh through the process in waves lasting months. [A recent Ph.D. thesis I helped supervise attempts to model these waves: "A Predictive Model of Sequential Iteration in Engineering Design," by Robert P. Smith, MIT Sloan School of Management, 1992.] The designers do not realize that this truly dynamic oscillation is due to their own actions, and they blame management for constantly changing its mind. "No one has an overall view of the process," said Ahlen. This too is typical of large design processes, as I can report from personal knowledge of research MIT has done in several U.S. companies.

To counter this set of problems, Larsson's people have been constructing information flow maps for complex designs. Their first attempt was quite complex itself. It shows an entire power train, part by part and system by system, seeking to represent how each affects the others (geometry, force, heat) as well as how it affects the customer (noise, power, smoothness). This diagram helped the designers to understand some of the interactions but it did not help with making the process more efficient.

To get a more specific model, the team has focused on single parts and will move back to whole systems later. Two projects were described, one for a connecting rod and one for a steering knuckle. Both are critical engineered parts where weight, strength, and safety are vital issues. The design process for each was cut from typically 40 weeks to 20 weeks or less. They are now confident that similar reductions are possible everywhere at the single part level.

I got some details about the steering knuckle project (Fig. 1). This formerly was a long and highly iterative part to design for two basic reasons. First, some design decisions had to be revised after the supplier was chosen. Second, some design details often led to the need for careful hand finishing of the parts to avoid stress concentrations and possible field failures. Both of these caused extensive delays while the part was redesigned and reanalyzed.

The supplier-related problem is interesting. The part is forged, and the issue is to choose the draft angle of the forging die. This angle is directly transferred to the finished part, so any finite-element method (FEM) analysis will be affected by choice of draft angle. These analyses take a long time, and redefining the CAD model to change the angle also is cumbersome. Unfortunately, the supplier who won the contract often could not deliver at the original draft angle (smaller angles are harder to achieve), thus the lengthy design and analyses had to be done over. To avoid this iteration loop, the integrated engineering team had to convince the purchasing department to permit the supplier to be chosen early in the design process, before a design existed and thus before the supplier could bid. Competitive bidding is thus ruled out. The net effect is still a win for Volvo as the result of the reduced design time.

Figure 1 is thus a time/technical structure, rather than a pure schedule. It is, however, only a summary of the detailed information that the team developed and hardly reveals the depth of understanding they had to reach. About 30 skilled and experienced people were required. Larsson's people facilitated the discussions, aiming to find a linear path through the design decisions. In particular, the things they did appear to me to have been:

- identify all the necessary design steps and the information they require and generate;
- find where this information is really available (not just at the official end of a given step in the process, but often earlier in that step);
- find sources of iteration and identify the real reasons;
- find opportunities to work in parallel;
- find long-lead-time items and try to start them earlier (noting that the information they will need must also be provided earlier);
- find precedence chains that can be broken so that tasks can be resequenced (this

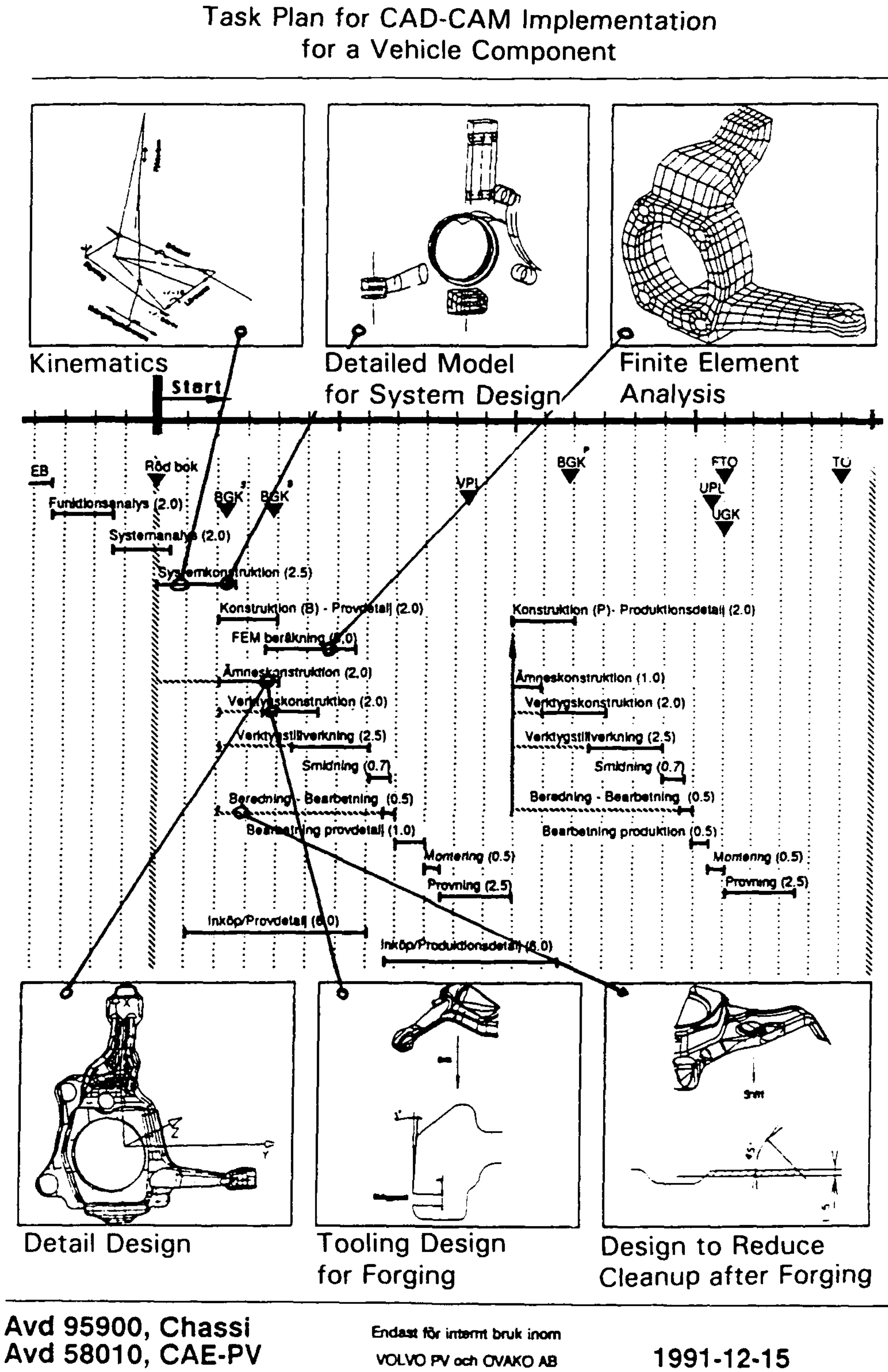

Fig. 1—New schedule for designing and prototyping a steering knuckle, showing key information and when it needed. This is a schematic schedule for the design, development, and testing of a car steering knuckle. It was prepared by the Volvo CIM team to present to its management the results of studying and drastically shortening the knuckle's design process. The schedule shows several tracks ongoing in parallel. The schematic also shows the kinds of information needed at various stages of the process. (Courtesy Volvo Car Corporation. Used by permission.)

requires classifying constraints, much as Nippondenso does, into "must have," "would like," "due to physical law or material property," and so on); and
- find ways to design-out problems that will take a long time during manufacture and assembly (note that a wasted minute making each of a million parts adds up to a lot of time, more than may be needed during design to avoid the waste).

Larsson notes the following about such efforts. First, the 50 percent time reduction can be credited about half to resequencing the tasks and half to using new computer tools to accomplish each step faster. Second, the main thing is to understand each design process in detail "from the bottom up," admitting that each one will be different for technical reasons. These specific reasons (such as the critical need to choose the draft angle after the supplier is chosen) may not be transferrable to another part. Third, people with expertise in this process must accomplish the redesign of the process. BUT, since these people rarely believe that the process can be significantly speeded up, outsiders are necessary to make the process redesign happen.

I should add that the effort to rationalize the process is usually necessary before many of the computer tools can be written. Otherwise one will not know what information to provide for them. The same thing was discovered years ago about automating manufacturing operations: don't automate the existing manual process.

At the moment, there are few engineering models to back up the information flow model. Body engineering is ahead in this respect, as is body engineering's overall sophistication. "A few people there understand the whole process." Additionally, there are no systematic tools available for helping people who want to model and redesign design processes. [My colleagues at MIT and I have developed some ways of diagramming design processes that permit systematic rearrangement of task sequences to be done. However, the main tool is still personal interviews and hard thinking. Reference 1 describes this.]

Existing methods such as PERT/CPM are mainly scheduling tools that model the process as once-through-each-task, thereby ignoring iteration. Also, they have no technical information content, only start and stop times and simple task precedences. The IDEF modeling method, developed by the Air Force about 15 years ago, creates a hierarchical model of information flows, but it is so complex that people who did not participate directly in making the model cannot understand it. The new European CIM-OSA model, part of a huge ESPRIT program, creates models that look a lot like IDEF models. These, too, are made manually by interviewing the participants. Reference 2 describes a capstone industrial project developed by a university student.

ORGANIZATION OF CONCURRENT ENGINEERING PROJECTS

In the last two years Volvo has fully adopted the project method for designing cars, using the "heavyweight manager" method identified by Prof. Kim Clark of Harvard Business School. Each project "buys" engineers and, sometimes, components like engines from the engineering divisions of the company. These people stay with the project and have only one project to work on at a time. Some companies do not know whether it is better to focus engineers this way or to let them work on several projects at once. Volvo has found that engineers on a single project focus on reducing the design time, whereas those on several projects tend to emphasize technical excellence in their individual parts of the design.

Volvo has established a technical center where most of this design activity takes place. It includes styling, engineering, manufacturing engineering, and prototype production lines. But true collocation of all the activities cannot be accomplished on all projects because Volvo is too small and must form partnerships with other companies around the world. This is complicated by incompatibility of data and by the fact that other car companies are not as advanced in computerizing their design processes.

CONCLUSIONS

The Volvo people I met are quite sophisticated and have accomplished a great deal that other companies I know have not yet tried. Their efforts show that the problems of designing large and

complex things require new views of the relationships between information, engineering, planning, and computing. I believe that several of the large Japanese companies I visited also understand this and have begun the process of really computerizing their design methods.

However, no one, not even the Japanese, have systematic methods for accomplishing this. There are two basic gaps. First, processes for designing things need to be better understood and modeled. I really think that many people do not understand how to design the things they are designing. That is, they do not understand the process in terms of what decisions are actually needed, when they are needed, what input information they require, what are the consequences of a bad decision, and so on. Second, the technical underpinnings of many designs are not well understood, except in the heads of experts who have found out by trial and error. This is less of a surprise, since the limitations of engineering models are widely recognized. The evidence for this is huge efforts to simulate complex things on computers or to build expert systems and neural nets to "capture the expertise." The combined result of these two gaps is that when one wants to "computerize a design process" one is often left linking human experts by electronic mail.

Furthermore, the current bottom-up efforts to streamline individual design processes have not yet yielded much general knowledge about such efforts except the observation that "each one is different." This is a sure sign that research is needed, since the claim that each one is different often can be countered once some general principles are teased out of the examples. The fact that outsiders (sometimes even university students) can diagnose individual projects gives hope that research will be successful.

REFERENCES

1. S.D. Eppinger, D.E. Whitney, R.P. Smith, and D.A. Gebala, "Organizing the Tasks in Complex Design Projects," in *Proceedings ASME Design Automation Conference: Design Theory and Methodology*, Chicago, Sept., 1990, Vol. DE-27, pp 39-46.

2. P. Vaes, "CIM-OSA Case Study of the IC-Route," ECIM Department, Hogeschool Eindhoven, May 1991.

Point of Contact

Kurt G. Larsson
General Manager, Computer-Integrated Manufacturing
Volvo Car Corporation
S-405 08, Gothenburg Sweden
Phone: + 46 31 59 16 14
Fax: + 46 31 53 13 84

Materials

Quality Research and Productivity—The Dutch Treat

by Joseph H. Magill, Liaison Scientist for Polymeric Materials for the Office of Naval Research European Office. Dr. Magill joined ONR Europe from the University of Pittsburgh, where he held Professorships jointly in Materials Science and Engineering and in Chemical and Petroleum Engineering.

KEYWORDS: synthesis; blends; fibers; thin films; devices

INTRODUCTION

Dutch universities are among the youngest and oldest in Europe—their ages spanning from a quarter of a century to almost four centuries. Whatever their age, the universities are dedicated to quality education and research, providing graduates with both a well-rounded education and specialized training at the graduate level. Students are encouraged to cross academic boundaries in pursuit of

their educational and research goals. As a country they produce high-quality research and productivity, and have built "good bridges" with industry that support research and applications of mutual interest. Research studies are funded by the government. In polymeric and materials sciences they can boast of high technology in many endeavors, and they often cooperate internationally with the best institutions in the United States, Germany, France, and the United Kingdom. They also participate in various European Community (EC) programs, including:

- COMMETT - Community Action Program for Education and Training for Technology,
- DRIVE - Dedicated Road Infrastructure for Vehicle Safety in Europe,
- BRITE - Basic Research in Industrial Technologies for Europe (to stimulate European research and education), and
- SCIENCE - a program to develop cooperative research centers, laboratories, and universities on specific subjects.

Dutch universities also have interuniversity programs with Central and Eastern Europe.

These traits were manifested during my recent visit to polymer science laboratories at the University of Twente, University of Eindhoven, and the University of Groningen. Departments are well populated with students and researchers in polymers and materials; a few Russian research workers were recently involved. Interestingly, a polymer technology center with government funding is being instigated for The Netherlands. This center will involve the three universities previously noted and also the University of Delft. The industries that will be involved along the with the research and development (R&D) work force (numbers in brackets) are: AKZO (1500), DSM (1500), Philips (5000), GE Plastics (150), Shell (2000), DOW (500) and GE Plastics (150). In this article I concentrate on research activities at the Universities of Twente, Eindhoven, and Groningen. Individual universities will be described in more detail in future *ESNIB* reports.

NANOSCIENCE AND NANORHEOLOGY

Both of these areas feature in current research programs from both fundamental and technological viewpoints. Atomic force microscopy (AFM) is the preferred instrumental technique for most polymers, scanning tunnelling microscopy (STM) being more useful for conducting materials. Research at Groningen and Twente Universities have demonstrated resolutions equivalent to several tenths of a nanometer. Here, Professor George Hadziiannou (formerly of IBM, now at Groningen) and his students are very active in using AFM to characterize surfaces/interfaces because of a strong interest in nanorheology. One of the thrust research areas (academic and applied) is concerned with new lubricants. AFM is being used to measure the forces perpendicular and transverse or along the polymer chains, for example. Special charged sensing probes are being developed and used for this purpose.

SYNTHESIS (WITH DESIGN)

Professor Jain C. van de Grampel and his associates (University of Groningen) have successfully made phosphazene-substituted polysiloxanes having phosphazene cyclic pendant groups as the side chain. Acrylate and methylacrylate substituted cyclo-phosphazenes have also been synthesized; this has provided a class of stable, hybrid inorganic-organic polymers. These pendant groups can polymerize further by design to produce a high-temperature hybrid polymer with good flame-retardant properties if and when the cost is right. With an eye to good science and development also, Professor Martin Möller and associates (University of Twente) have synthesized and characterized mesomorphic polysiloxanes and polysilanes. Like polyphosphazene homopolymers, they form mesophases that are the basis for the development of macromolecular engineering concepts in a controlled way. Möller et al. have made polymer surfaces modified by fluorocarbon-hydrocarbon substituents. Since the fluorocarbon is segregated to the copolymer surface, it has a low surface energy (not unlike teflon). Interestingly, AFM shows regularly

arranged "rows" or elevated topological features assigned to—CF_3 end groups in real space at resolution less than one nanometer. These surface features can also moderate solubility.

THIN FILMS

In this area, significant ongoing work is being conducted by Dr. A.J. Schouten's research group at the University Groningen by using Langmuir-Blodgett (LB) monolayers and multilayers. They have concluded from detailed work that

- (by using poly(isocyanides) with different side chains) rigidity of the polymer backbone alone is not sufficient to determine stable films at the water-air interface; polar groups also play a significant role.
- mobility of the grafted polymer is inhibited for specimens of the same molecular weight (this is concluded from the interdiffusion results of free and grafted poly-(methylmethacylate (PMMA) with poly-(vinyl chloride) or silicon). This study has practical significance in polymer adhesion.
- the monolayer behavior of PMMA is strongly dependent on the tacticity of the backbone and is dictated by the dipole moment in syndiotactic PMMA being smaller perpendicular to the water surface than it is in atactic PMMA, for example. Additionally, isotactic polymer is stable on pure water subphases, whereas syndiotactic PMMA is not. Amylose-polyesters also have features that are conformationally distinguishable. A knowledge of these facts are important when the L-B technique is used for epitaxial crystallization preparations. An understanding of molecular conformation is essential where L-B techniques are used to produce nonlinear optical (NLO) devices, which was an interest of this group for the AKZO Corporation.

PHOTOREFRACTURE MATERIALS

Characterization and synthesis in nonlinear optical materials feature in investigations at both the University of Groningen and the University of Twente. A sophisticated electro-characterization laboratory is being set up at Groningen (George Hadziiannou's group) to explore a range of doped co-polymers that fluorescence. Commercial applications of these materials are well known for information processing, holography, and transistors (to name only a few).

The overall objective is to have larger storage capability and shorter response time in "high tech" devices.

POLYMER BLENDS

Research in this field features strongly in the R&D work at the University of Eindhoven, where aging and the mechanical behavior of polymers, copolymers, and composites are of great concern. Dr. Gerrit ten Brinke helped pioneer some of the advances in phase behavior investigations in homopolymer blends and random copolymer blends in the early 1980s that use "mean field theory" in the analysis of these systems.

Reasons for miscibility and immiscibility "windows" for polymer blends to processability polymers are based on thermodynamic considerations is essential. Criteria have now been developed and used successfully on a predictability basis to describe polymeric behavior. Ongoing investigations embody studies of polymer flow in a good solvent by using Monte Carlo simulations of self-avoiding random walks that are modeled on a cubic lattice. Experiment and theory are in reasonable accord.

For more complicated systems of thermostats and engineering, thermoplastics blending is still an "art/science" topic that is being studied at the University of Eindhoven by Professor Pete J. Lemstra and associates. Aspects of measurability of phase separation, rheology, cure conditions, morphology, mechanical properties (including toughness) and their role in composite structures have to be tackled in a more practical (rather than theoretical) fashion. In some types of modeling here, the real world and basic sciences hardly mix except to provide an operational hypothesis, in its broadest sense.

FIBERS

Professor Albert J. Pennings of the University of Groningen is well known internationally for

having pioneered the spinning of ultra high molecular weight polyethylene (UHMWPE) and other polymers to prepare ultra high modulus strength fibers. Detailed studies of morphology-property-processing correlations have been made, and the variables have been elucidated for processing. In general, UHMWPE fibers average 7.2 GPa tensile strength, 265 GPa tensile modulus, with elongations at a break of 3.5%. On a specific basis, these properties are superior to most metals—including steel! Now that the Couette spinning process is being used for processing biodegradable poly (L-lactide) and other systems, there are obvious applications in the biomedical and bioengineering area.

At the University of Eindhoven, Professor Pete J. Lemstra and his associates have developed the gel-spinning of UHMWPE, which is now a well-known commercial polymer success being used by DSM, Geleen, The Netherlands, and at Allied Signal Corporation, N.J. By way of contrast, the new high-speed spinning method of Prof. Pennings so far has produced only fibers of inferior mechanical quality compared to those made by the classical Couette technique just mentioned. Apparently, there are morphological reasons for the substandard properties of these fibers, and they are still being explored. The University of Eindhoven is impressive in its technological activities. Everywhere good interaction is occurring in science and technology—across departmental lines within institutions and through interactions with industry; universities in The Netherlands are to be applauded.

CONCLUSIONS

Research and productivity on polymer at these Dutch universities is distinguished and often in tune with important technological problems. Overall, the programs are more focused on quality science than on fierce competition to be first in the field, although this also is important. In fulfilling their mission, the graduate students and faculty are well informed—a fact that is evident on reading any Ph.D. student thesis.

Oceanography

U.K. Contribution to Climate Research: The Rennell Centre for Ocean Circulation

by John P. Dugan and Thomas H. Kinder. Dr. Dugan is an oceanographer currently serving as Liaison Scientist for Physical Oceanography at the Office of Naval Research European Office; previously he formed and directed the Field Measurements Department at Arete Associates. CAPT T.H. Kinder, USNR, was a visiting scientist/reserve officer at the Office of Naval Research European Office; he is Manager, Coastal Sciences Program, Office of Naval Research, Arlington, Virginia.

KEYWORDS: oceanography; Rennell Centre, marine meteorology, air-sea interaction; deep-ocean circulation

INTRODUCTION

Is it true that increased CO_2 in Earth's atmosphere really will cause the earth and oceans to warm, thus melting the ice caps and raising the level of the sea over much of our present-day coasts? This is the question being addressed by a large international group of oceanographers and atmospheric scientists. It should not come as a surprise that the uptake and release of heat by the ocean, which is controlled in large part by the resulting circulation, is a dominating influence on

our climate. Unfortunately, our knowledge of ocean circulation and what controls it on the time scales important to the climate (decades and longer) is inadequate. Because of this lack of knowledge, the world body of ocean scientists have organized the World Ocean Circulation Experiment (WOCE), a ten-year program to improve our knowledge about the circulation and its interaction with climate. The United Kingdom (U.K.) has contributed a special multi-year grant from the Natural Environment Research Council (NERC) to the Institute of Oceanographic Sciences Deacon Laboratory (IOSDL) to study aspects of the ocean circulation.

Oceanographic research in the U.K. is organized into a number of centers of excellence in specific research and technology areas, one of which is IOSDL. The James Rennell Centre for Ocean Circulation was founded as part of IOSDL with the objective of being the premier research organization in the U.K. for deep-ocean circulation research. Reference 1 describes its opening and initial activities. The Centre is the focal point for U.K. contributions to WOCE, and it has major thrusts in collecting appropriate data sets, performing analyses of the data, and constructing models of the ocean. The Centre is located temporarily in the Chilworth Research Park which is on grounds owned by the University of Southampton in the suburbs of Southampton. It will relocate to the Southampton Centre for Deep Sea Research, which presently is under construction and is scheduled to open in 1994. The new Southampton Centre is located pierside in Southampton harbor on the south coast of the U.K. The Rennell Centre will share space with the Oceanography and Geology Departments of the University of Southampton (the parent organization) and remaining divisions of IOSDL, which presently are neai Wormley in Surrey, and the Ship Services Department, which will relocate from its present location in Barry on the west coast of Wales.

U.S. NAVY INTEREST

It may seem that research into the future of Earth's climate is remote from the needs of the U.S. Navy. However, there is a direct relationship between the oceanographic research that is supported under this program and Navy needs. Specifically, an understanding of the physical, chemical, and biological processes and dynamical mechanisms that occur in the ocean is required in both cases—the fundamental truths affect each of them. In addition, as recently stated by the Oceanographer of the Navy, Rear Admiral Chesbrough, "We have progressed to a complexity and sophistication wherein the determining factor between victory and defeat may well be exploiting our knowledge of the environment,"[2] and that knowledge is to be found in the major oceanographic, ocean physics, and marine meteorological institutions in the world. This work contributes directly to that knowledge base.

ORGANIZATION OF THE RENNELL CENTRE

The Director of the Rennell Centre is Dr. Raymond Pollard, who is well known for his fundamental observational research in air-sea interactions—particularly for his organization of the Joint Air-Sea Interaction Experiment (JASIN), which was undertaken in conjunction with the flight of the NASA SeaSat ocean-observing satellite in 1978. Dr. Pollard administratively reports to Dr. Colin Summerhayes, the Director of IOSDL. Since the Rennell Centre was set up as a result of special funds available from NERC for deep-sea circulation studies in support of WOCE, the activities are dominated by work associated with that international project.

To support this work, the Centre has about 50 employees who are organized into six research teams that coordinate activities in their specialties. These teams are the Survey, Chemical Tracer, Meteorology, Satellite, Physical Modeling, and Biological Modeling Teams.

The primary activity of the Survey Team is support of frequent field trips to acquire, process, and archive oceanographic observations, primarily ocean density and velocity data. The Chemical Tracer Team supports studies of the oceanographic circulation and physical processes by observations of the distribution of chemical substances. These include natural ones such as oxygen, silicate, phosphate, and nitrate, but also include anthropogenic ones like radionuclide contaminants and chlorofluorocarbons. The Meteorology Team develops methods for measuring the fluxes of momentum,

heat, and water between the sea and atmosphere. The Satellite Team develops methods to estimate the ocean circulation and atmospheric forcing from space, taking advantage of the major oceanographic satellite missions either already launched or to be launched in this decade. Specific measurements include surface height, temperature, fluxes, and wind stress. Finally, the modeling teams use the observational data to develop and calibrate models of the circulation and of the carbon flux. These activities may seem diverse to the uninitiated, but they are coupled by mutual needs to support the goal of understanding the ocean's circulation and its interaction with and affect upon the climate.

Although this global view of oceanography dominates the activities of the Centre, research is pursued on related oceanographic problems that are not specifically supported by the NERC funding related to WOCE. One significant and important project, which also is important to WOCE, is understanding the mixing processes that distribute the water properties vertically and laterally; one component of this is the effect of mesoscale features typically called fronts and eddies. One of many issues is: how does a mesoscale eddy actually mix properties across density surfaces, and how efficient is this process compared with other possible causes of mixing such as internal wave breaking or diffusive convection?

SURVEY TEAM

SeaSoar

The Survey Team has advanced the state of the art of observations of the physical properties of the ocean with a unique underway measurement capability that has been developed at IOSDL over a number of years. This technology has evolved into the SeaSoar platform that now is available commercially. SeaSoar is a towed vehicle that is flown up and down in the water column by moving controllable wings while the ship is underway at speeds of about 10 knots. The vehicle can carry a conductivity-temperature-depth (CTD) instrument that transmits data to the ship, providing vertical profiles of these parameters approximately once every 3 km in distance traveled. These measurements are used to calculate profiles of temperature, salinity, density, and sound velocity. This provides sufficient resolution in space to resolve the influence of mesoscale features in the upper ocean such as fronts and eddies. Most importantly, it is able to do this without the time-consuming, traditional method of stopping the ship and deploying the CTD in a profiling mode while the ship is drifting. In one recent six-week deployment, the system acquired continuous profiles along 12,000 km of ship track.

The towed vehicle also has the capability to mount other instruments that can be powered and operated remotely. Examples are sensors that measure dissolved oxygen and chlorophyl a, the latter being a measure of the biological primary productivity. This towed sensor technique has proven to be so reliable and conservative of ship time that there is considerable interest in the rest of the international oceanographic community in also having this capability. The vehicle design has been licensed to Chelsea Instruments Ltd., and they have sold about 10 of these devices worldwide. Unfortunately, they have not been as reliable for other users, and there is keen interest presently in many institutions in several countries in upgrading the vehicle, its mechanics, and the controls.

In one activity to support this community, the Rennell Centre hosted a workshop with about 20 attendees from Australia, the U.S., and the U.K. in June 1992. The objective was to decide on a reasonable path for upgrading the vehicle for use in the next decade. Important briefings were given on descriptions of concerns with the hydraulic drive mechanism, the cable fairing, and the control system. In addition, important advances were also described to the attendees on computer control of the vehicle and on the handling of the massive amounts of data that are acquired with the typical sensor systems installed in it. The results have been distributed to interested parties, and an electronic bulletin board has been set up to enable improved communications between the international community that is interested in this project. The board is on OMNET and is called SEASOAR.USERS.

Acoustic Doppler Current Profiler

In addition to the towed vehicle, the research vessel also can carry other instruments such as an acoustic doppler current profiler (ADCP) that

provides vertical profiles of the horizontal current over the topmost 300 m or so of the ocean. The present instrument was purchased from RD Instruments of San Diego (standard 150 kHz unit), but IOSDL has been a technological leader over the last decade in the use of acoustics for measuring currents from moored instruments and from ships while underway. At one time, they used a number of units that were designed, constructed, and deployed by the IOSDL Ocean Instrumentation Group. The operating principle of the current profiler is the doppler shift of the acoustic beam caused by the movement of scatterers in the water relative to the beam. Typically, the scatterers are assumed to be stationary in the water, so that their motion is representative of the water velocity.

From analysis of the data from both shipboard and moored ADCPs, the Survey Team has learned that the strength of the acoustic return also is interesting—it retains important information on the reverberation in the water column. This is interpreted to provide information on the distribution of zooplankton biomass and vertical migration in the water. The wavelength of the acoustic signal is about 1 cm, so the particles most contributing to the backscatter are expected to be micronekton, e.g., euphausids and amphipods and possibly large copepods. The scientists have found interesting results on the temporal and spatial patchiness of the scatterers, diurnal vertical migrations (order 100 m/hr) and, in conjunction with the SeaSoar data, relationships with hydrography and nutrient and chlorophyll profiles. Especially interesting are locations of what appear to be upwelling and downwelling zones associated with mesoscale eddies.

Data Analysis Schemes

Finally, the Group has developed unique data analysis schemes. A data processing system has been developed for acquiring, editing, calibrating, and archiving the data from the instruments on the SeaSoar vehicle and the ADCP. It includes impressive color graphical displays and incorporates arbitrary 2-D cuts through the 3-D results. In addition, they have developed a specific technique whereby they estimate the (very small) vertical water velocities associated with mesoscale motions. This is important because these vertical motions are a candidate for vertical mixing as they upwell deeper water to the vicinity of the surface or ventilate the thermocline through ingestion of water from the mixed layer.

Surveys and Results

Surveys have been conducted in the FASINEX region (near 28N, 70W, site of the ONR-sponsored Frontal Air-Sea Interaction Experiment), near the Iceland-Faeroes front, and in the U.K. Vivaldi region (near 49N 35W, site of the U.K. WOCE seasonal evolution experiment). For the FASINEX data, the deep ADCP velocity data are used to form a streamfunction at 150 m depth, and then the SeaSoar density data are used to extrapolate vertically upwards. A meteorological technique is then used to infer vertical velocity from nearly geostrophic flow fields. The so-called omega equation can be solved for vertical velocity as a function of spatial gradients of the geostrophic (horizontal) velocities. This requires well-resolved velocity and density measurements and careful processing of the data to preclude contamination from inertial currents. The scheme was highly successful in the FASINEX data because of the observed linearity of the surface front that was under study.

It has been found that sub-mesoscale eddies are associated with vertical velocities of up to 40 meters per day, a number that is reasonable (but is too small to be measured directly above the instrument noise level exhibited in the ADCP data). In the Iceland-Faeroes work, the calculated vertical velocities were confirmed, at least in general location, by the cross sectional distributions of chlorophyll as measured by sensors on the towed vehicle. Indicated regions of upwelling showed marked increases in productivity as mineral-rich water was brought up to the euphotic zone. Dr. Pollard suggests that these mesoscale structures may be common in the world ocean and is writing a summary paper that discusses evidence for their widespread occurrence. If this is true, he further argues that these features must be important in conditioning the surface boundary layer dynamics and in imposing scales on the lower trophic levels in the upper ocean.

METEOROLOGY TEAM

The Meteorology Team is headed by Dr. Peter Taylor; its research focuses on how the ocean controls and responds to the weather in the atmosphere. This interaction between the two media is driven by the fluxes of momentum, heat, and water, and their values are needed in the research at the Centre—both for driving ocean models and for verifying climate models of the coupled ocean-atmosphere system.

Needs and Capabilities

Satellites are expected to aid measurement of some of these fluxes because only they will have the required global coverage. However, there is a significant gap between this need and the present capability, with much development presently underway in the derivation and testing of retrieval algorithms to calculate these parameters from the satellite observations. The only present capability for numerous observations is based on ships of opportunity and freely drifting buoys. It is expected that these in situ data will still be needed in the future to help determine the heat and water fluxes, to provide historical continuity, and to verify satellite observations.

This group has two interesting programs associated with this general problem (in cooperation with the IOSDL Ocean Instrumentation Group). It has developed and fields a sensor package called MultiMet that can be mounted on the mast of a ship and measures all important meteorological variables associated with these fluxes. This includes high-frequency velocities, from which the stress is estimated through the dissipation method. This is a controversial method because of problems associated with both the motion of the ship and also blockage of the flow by the presence of the ship. These issues are being carefully addressed, and the answers are not all in at present. In the meantime, the package is used during all deployments of the Survey Team.

Voluntary Observing Ships (VOS)

The second major research issue that this team addresses is maximum utilization of meteorological measurements from ships of opportunity. This is important because much that we know about the marine climate is based on observations made at sea but, in addition, these ships provide data in oceanographic regions where there are precious few other sources of data for assimilation into the synoptic weather forecasting systems. Many of these observations are made from Voluntary Observing Ships (VOS) but, because these ships are merchant ships rather than specially designed meteorological research platforms, the data are subject to both systematic and random errors and biases. The enormity of this problem can be appreciated from the fact that there presently are about 7000 of these vessels reporting four times daily. Unfortunately, there has been very little sound information available on the nature of the VOS fleet or on the observing practices that are used, so the data have long been considered suspect.

The objective of the work in this team is to improve this situation by determining the effect of different observing practices on accuracy, and whether any improvement might be effected by reporting additional information or by changing the practices. Also, since the VOS are recruited by agencies of the national members of the World Meteorological Organization, an additional goal is to determine whether the different national (six countries in this case) procedures and preferences cause systematic biases in the data.

The work involves 45 volunteer ships that have participated in the Voluntary Observing Ships' Special Observing Project—North Atlantic (VSOP-NA) for about 2.5 years. This is a pilot study whose objective is to use a carefully controlled situation to quantify the systematic biases and errors in typical VOS data by widening the data collected beyond what are routinely collected. The normal data are wind speed and direction, air temperature, humidity, sea surface temperature, and atmospheric pressure. Additional data include details of the measurement technique(s) and the ship's speed and direction at the time of measurement.

The project has been coordinated with the Deutsche Wetterdienst (German Weather Office) and the U.K. Meteorological (Met) Office, with the former transcribing the ships' data for a limited trial period. The Met Office has merged the observations with the corresponding variables output from the analysis stage of the fine mesh (limited

area) atmospheric forecast model (which has half the mesh size and twice as many analyses per day than does the global model), and is also participating in the subsequent data analysis. This analysis consists of calculating and comparing the mean differences between the observations and the model values at the time and location of the ship. The model values are considered to be a standard of comparison rather than an indication of "truth". This is a very good test, as overall mean differences would indicate a bias between observations and model, whereas relative differences between ships would indicate relative biases.

In addition to conducting normal observations, the Ocean Weather Station vessel *Cumulus* has been equipped with a MultiMet automatic reporting station, which was maintained by the Rennell Centre, as a check on the data. In total during the trial period, about 25,000 observations were in the final quality-controlled data set, and they are available to other scientists from World Data Centres A and B.

The insightful reader will notice that there is a small bias in the test using the analysis model data because the Met Office actually uses some of the VOS data in the analysis. However, this is considered a small effect because of the low reliability typically put on VOS data during the data assimilation phase. Also, only pressure, wind, and sea surface temperature are used in the analysis.

Results and Conclusions to Date

There are a large number of results and conclusions to date. Compared with the observations, the model exhibits significant deviations, with model air temperature being higher in cold regions and vice versa, model humidity observations drier in low humidity but moister elsewhere, and model wind speed being biased low by more than 2 m/s. The characteristics of different types of instruments for measuring air and water temperature are apparent in the reported measurements, and there are significant correlations with wind speed. Finally, fixed anemometer measurements are consistently higher than Beaufort estimates made by ships' watch officers.

The results enable recalibrations to be calculated for each ship, and the data thereby modified, thus improving each ship's contribution to the whole data set. Recommendations have been made to the WMO regarding the standard practices for ships of opportunity.

CHEMISTRY TEAM

Tracers

The Chemistry Team is a small one of three scientists headed by Dr. Denise Smythe-Wright. Its primary goal is to use chemical tracers in the ocean to study physical oceanographic processes and their effects on the circulation. The variations in the concentrations of chemical constituents are useful because they average out time and space variability and provide information that is averaged over long periods of time. The ultimate goal is that a comprehensive data set will enable the extent, rate, and variability of water mass sources and the processes of their modification to be determined, and that an integrated value on the circulation of water on a global scale will be acquired .

The measurements are being focused on: oxygen; the nutrients silicate, phosphate, and nitrate; the chlorofluorocarbons CFC-10 to 13; and plant pigments. The CFCs are particularly useful in calculating the time that has elapsed since a particular parcel of water was last in contact with the atmosphere, so they provide a time dimension to the penetration of water masses into the ocean interior. All measurements are made at sea by analytical methods. To date, the group has collected a full suite of measurements during the VIVALDI and CONVEX cruises.

MODELING TEAMS

The ultimate aim of the research at the Rennell Centre is to clarify the uncertainties about the role of the ocean in controlling our climate. This goal will only be attained if suitable models of the ocean/atmosphere system can be constructed so that predictions can be made of what will happen under present and future anthropogenic inputs to the system. At the Rennell Centre, this work is split into physical and biological modeling teams.

Physical Modeling

The physical modeling team is headed by Dr. Adrian New. The goal is to implement physical models of the ocean circulation and to test the response to changes in the input. The team is testing the importance of mesoscale eddies to the circulation and the effect of deep mixing in subpolar regions, and assessing the relative merits of different types of model formulations.

A current project is implementing a North Atlantic (80N to 20S) isopycnic ocean circulation model (naturally called AIM, for Atlantic Isopycnic Model). Isopycnic coordinates are expected to be more "natural" than the more usual models that have fixed grid levels in the vertical, since water parcels move most easily along (or close to) such surfaces where the buoyancy forces are negligible. Traditional ocean circulation models have either vertical or contour-following (so-called *sigma*) coordinates. The model presently has 0.5-1.0 degree resolution and 19 layers. There is a "pseudo-ice" model, where surface fluxes are set to zero when temperature is below -1.8 °C. Surface fluxes use the "Haney" condition, where they are driven by departures from climatological temperature and salinity to regress toward climatology. At present there is no Mediterranean outflow, and there are solid walls at the northern and southern boundaries. A sea surface temperature anomaly in the results of a 30-year integration is thought to be caused by the absence of diapycnal mixing, which he plans to add. At present, Dr. New is cooperating closely with Ranier Bleck, University of Miami, who originally designed the model. Eventually, model results will be compared with a Bryan-Cox (vertical coordinate) model being run at the Hadley Centre of the British Meteorological Office.

A number of simulations have been run on the Hadley Centre supercomputer for time periods as long as 60 years. Several of them have varied the haline forcing and the bathymetric roughness to test the sensitivity to these input fields. It has been found that the isopycnic model permits much rougher bathymetry than does an equivalent Bryan-Cox simulation, but the difference on basin-averaged northward heat flux is only about 5 percent. Also, Labrador and Greenland Sea Deep Waters are produced by convection and exported in an equilibrium state, and their identification and quantification is simplified by the isopycnic technique. The model will shortly be implemented on the Rutherford Appleton Laboratory Cray at eddy-resolving scale, and improvements will be implemented on diapycnic mixing, relaxation of surface boundary conditions, lateral boundary conditions, sea ice modeling, and deep convection. A primary issue still to be resolved is the necessity for resolving the eddies, or whether these can effectively be parameterized in the model.

Biological Modeling

Recent concerns about the effects of anthropogenic emissions of CO_2 and their effects on our climate have raised the level of importance of biological processes because marine biota are intimately involved in the cycles of nutrients and carbon within the ocean. The marine ecosystem is very complicated, with several important biological processes that are interconnected with physical and chemical processes. Work in this area is undertaken by the biological modelling team, and its goal is to develop biological models that predict the carbon fluxes between the atmosphere and the deep ocean. The team leader is Dr. Michael Fasham.

STATUS OF NEW BUILDING

As mentioned previously, ground has been broken for the new building, and construction has begun for the expected completion in 1994. The new location should fulfill the goal of promoting interactions between the university, the Rennell Centre staff, the other divisions of IOSDL, and the ship operations. The Southampton Centre has some but not all ingredients of a fully interdisciplinary oceanographic center. It also has space for shops, but there presently are no plans to include any specific technology groups beyond the Ocean Instrumentation Group of IOSDL in areas such as ocean acoustics or marine engineering.

NEWSLETTERS

Because of their expertise in various areas and the rapid developments in oceanography and ocean instrumentation, Rennell Centre personnel publish several aperiodic newsletters, often in conjunction

with other organizations. The *Profiler* is a newsletter concerning the technology, science, and experience of European oceanographers with ADCPs. *SeaSoar News* is concerned with developments with that device and, although it is published aperiodically by Chelsea Instruments Ltd, the majority of the contributions are submitted by Rennell Centre personnel. *Sigma* is a newsletter that provides information and informal communications concerning matters associated with the U.K. WOCE program. Finally, the Office of Naval Research financially supports a newsletter called *Ocean Modelling* that publishes preliminary results of research in this area in the U.K. This newsletter actually is edited and produced at the Robert Hooke Institute in Oxford under the guidance of Dr. Peter Killworth and others.

REFERENCES

1. L. Jendro, "The Rennell Centre for Ocean Circulation," *ESNIB* **91-03**, 60-61 (1991).
2. ADM G.L. Chesbrough, "Wind and Waves Are Always on the Side of the Ablest Navigators," *Sea Technology* **32**(1), 19-23 (1991).

Contact

Rennell Centre for Ocean Circulation
Gamma House
Chilworth Research Centre
Southampton SO1 7NS
United Kingdom
Phone: +44 70 376 6184
Fax: +44 70 376 7507
OMNET: RENNELL.CENTRE

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE February 1993	3. REPORT TYPE AND DATES COVERED Multidisciplinary Research Bulletin	
4. TITLE AND SUBTITLE European Science Notes Information Bulletin			5. FUNDING NUMBERS
6. AUTHOR(S)			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Office of Naval Research European Office PSC 802 Box 39 FPO AE 09499-0700			8. PERFORMING ORGANIZATION REPORT NUMBER 93-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NAVSO P-3678
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE
13. ABSTRACT *(Maximum 200 words)* European Science Notes Information Bulletin describes research being conducted and ideas being developed in Europe and the Middle East as reported by scientists assigned to the Office of Naval Research European Office and guest authors. It is published 6-8 times per year, on an irregular basis.			
14. SUBJECT TERMS Engineering Manufacturing Materials Oceanography			15. NUMBER OF PAGES 86 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

CHANGE REQUEST

NAVEUR-ONR-5605/1 (Rev. 6-91)

FOR YOUR CONVENIENCE . . .

Government regulations require up-to-date distribution lists for all periodicals. This form is provided for your convenience to indicate changes or corrections. If a change in our mailing lists should be made, or if you want any of the ONR Europe publications abstracted in this issue and listed below, please check the appropriate boxes. Fold on dotted lines, being sure our address is on the outside, tape or staple the lower edge together, and mail.

1. ☐ CHANGE OR CORRECT MY ADDRESS EFFECTIVE IMMEDIATELY OR (date)
2. ☐ DELETE MY NAME FROM DISTRIBUTION LIST
3. ☐ PLEASE SEND ME THE FOLLOWING ONR EUROPE PUBLICATIONS

Corrected or New Address

Fold Here

Fold Here

FROM:

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL

FIRST CLASS PERMIT NO. 12503 WASHINGTON DC

POSTAGE WILL BE PAID BY DEPARTMENT OF THE NAVY

Commanding Officer
Office of Naval Research European Office
PSC 802 Box 39
FPO AE 09499-0700